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THESIS

AN EXPLORATORY ANALYSIS OF CORRECTIVE MAINTENANCE DURING EXTENDED SURFACE SHIP DEPLOYMENTS

by
G. Karl Werenskjold
September 1998

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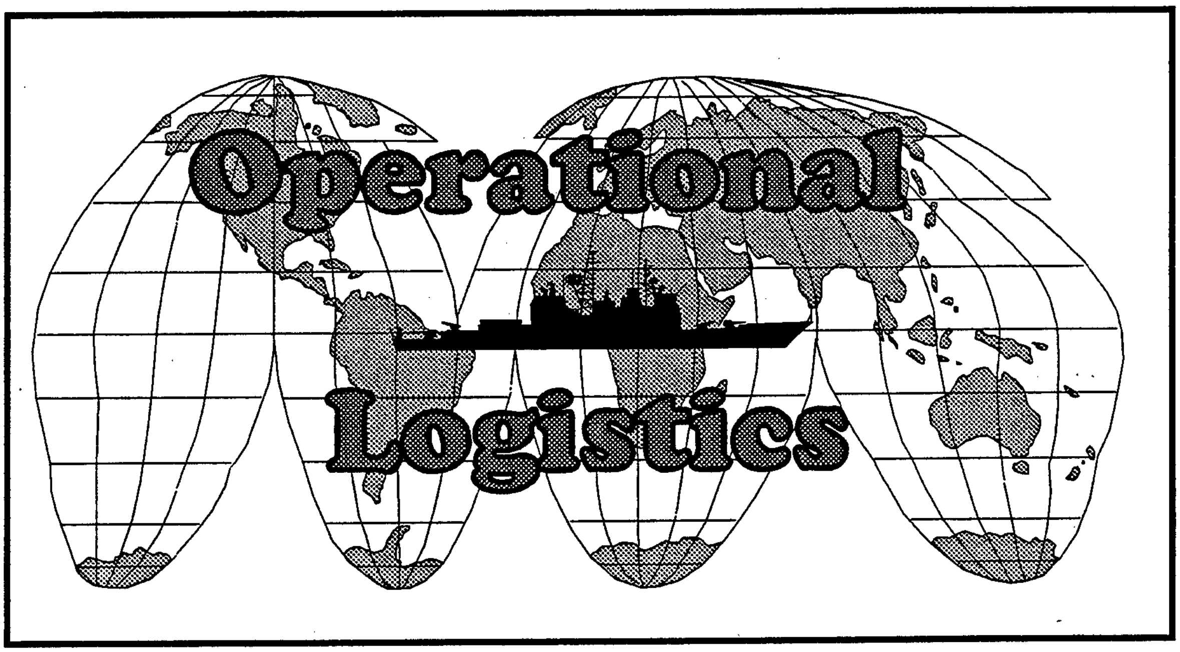
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13. ABSTRACT (Maximum 200 words)

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AN EXPLORATORY ANALYSIS OF CORRECTIVE MAINTENANCE DURING EXTENDED SURFACE SHIP DEPLOYMENTS

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ABSTRACT

This thesis illustrates the use of simulation techniques to evaluate the corrective maintenance requirements, and resulting operational availability on-station, for a ship deployed for an extended period of three years. The Chief of Naval Operations (CNO) Strategic Studies Group (SSG) in 1997 has proposed to deploy ships for three year periods and rotate crews. This concept is called *Horizon*. An object-oriented, discrete-event simulation is written in Java to simulate aspects of this extended deployment model. The simulation estimates the mean on and off station times of the ship, the mean time between shore-based repair, and the mean operational availability of the ship on station. The simulation allows a user to input as many ship systems with independent failure characteristics as desired, and evaluates a single-ship three year deployment. The simulation allows the user to perform sensitivity analysis on the input values to determine the significance of the results based upon the measures of the model. This thesis shows the effects of the inputs of the mean time-to-failure, logistics delay time, and percent of *organic* repair of the ship.

THESIS DISCLAIMER

The reader is cautioned that assumptions made with regard to the data used in this research are those of the author. Furthermore, although every effort has been made to ensure that the computer simulation program is free of computational and logical errors, it cannot be considered validated. Any application of information obtained from this thesis without further validation is at the risk of the user.

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EXECUTIVE SUMMARY

The United States Navy deploys its forces overseas to support the National Security Strategy core objectives. With the decrease in the level of overseas basing, the Navy will be relied upon more extensively to maintain an overseas presence. In 1997, the Chief of Naval Operations Strategic Studies Group XVI proposed an extended deployment concept known as *Horizon*. Within this concept, surface combatants (ships) are deployed for three-year periods, and the crews are rotated. The crew sizes of these surface combatants are planned to be greatly reduced, but it is proposed that technology fill the gap with remote sensors and better diagnostic equipment. Admiral Pilling, the Vice Chief of Naval Operations, has ordered that *Horizon* be carefully scrutinized to determine if any of its features should be implemented. This thesis explores the possible overseas corrective maintenance requirements of a single-ship three-year deployment using simulation techniques.

An object-oriented, discrete-event simulation has been written to evaluate how certain ship profiles perform during an extended deployment, and how marginal changes in subsystem capabilities would affect their performance. The primary inputs to the simulation are the systems and their associated failure modes. These failure modes model the demand for *inorganic* repairs required for the ship's systems during a three-year deployment. *Inorganic* repair requires the assistance of some outside facility or activity not resident with the ship; such repairs typically involve transit delays, during which the ship is off-station. In the past, *inorganic* repairs have been completed by overseas shore-based repair facilities, or by mobile ship tenders. Ship tenders have since been removed

from the inventory, and now all overseas *inorganic* repair requirements must be met by shore-based repair facilities. These shore-based facilities can be military facilities or contracted commercial facilities. However, section 7309C of Title 10, United States Code, prohibits ships homeported in the United States from being overhauled, repaired, or maintained overseas except for emergent repairs. The need for more overseas military repair facilities and mobile repair capability could become crucial if material readiness of deployed ships is to be maintained.

The primary outputs from the simulation are the mean on and off-station times of the ship, the mean time between demands for base repair, and the mean operational availability of the ship during a three-year deployment. The mean operational availability is the long-run percent of time that the ship is operating on-station. This gives an indication as to the *availability* of the ship to respond immediately to a random and unpredictable crisis. The operational availability together with the mean on-station time gives a good picture of the performance of the ship, and whether or not this performance is adequate enough to support the National Security Strategy.

Many analyses may be carried out using the simulation. The input parameters of the mean time between failures, the mean logistics delay time, and the percent of *organic* repair are manipulated to explore the sensitivity of the model to changes in their values. The model is sensitive to changes in the mean time between failures linearly, and has the largest effect on the ship's mean on-station time. However, the greatest degree of benefit is from attention paid to those failure modes with the relatively smaller times to failure, but cost should be a consideration. Once identified, these dominant failure modes are

candidates for re-engineering and reliability studies. Changes in the mean logistics delay also have a linear effect on the measures of the model, but mean off-station time is the most sensitive to this input. Again, the greatest degree of benefit is from decreasing the logistics delay of the dominant failure modes of the ship. The percent of *organic* repair capability of the ship's crew has a non-linear effect on the measures of the model. The mean time between base repair is the measure most affected by changes in the percent of *organic* repair.

How far a ship must travel in order to receive maintenance from an outside source has a significant effect on the off-station time of a ship. With ship tenders gone from the inventory, deployed ships must travel to and from a shore-based repair facility to receive *inorganic* repairs. If this transit delay is too long, the ship experiences a long off-station time, and the operational availability of the ship decreases as well. Developing a cost-effective mobile maintenance capability for deployed ships may be necessary to support the *Horizon* concept.

Logistics delays can be decreased using techniques such as ship-based sparing, express shipments, or shore-based inventories at overseas military repair facilities. *Organic* repair capability is improved through the use of better shipboard diagnostic equipment, direct links to technical experts such as the In-Service Engineering Agent or Original Equipment Manufacturer through a Logistics Network. *Organic* repair capability can also be augmented by the use of Fly-Away teams from military shore-based repair facilities. The overseas maintenance capability lost by the removal of mobile ship tenders can be restored with an increase in the capability of these Fly-Away teams.

The distribution of the failure modes has an effect on the output of the simulation *only* for strong degrees of "wear-out". Weibull times-to-failure with shape parameters greater than 1.2 result in longer mean on-station times, longer MTBBR, and higher mean A_o than the exponential case. Strictly using exponential distributions underestimates the measures of effectiveness of the model. Failure modes with weak degrees of "wear-out" (i.e. shape parameter of 1.0 to 1.2) or "near-birth" (i.e. shape parameters of 0.8 to 1.0) can be approximated closely with the exponential distribution.

This simulation assists in evaluating the trade-off benefits of increasing the logistics support, reliability, or percent of *organic* repair of a ship during a three-year deployment. This simulation can be used to test policies such as when to send a ship into port for repairs to gain an increase in the mean on-station time of the ship. And finally, in the future, this simulation can assist in determining the location and capability of shore-based maintenance facilities based upon the *inorganic* repair requirements of a single-ship or multiple-ship scenarios for a three-year deployment.

Horizon is a concept which may revolutionize the way the United States Navy performs surface ship deployments. But the primary restriction of this concept is the unknown demand for *inorganic* repairs, and the possible shortfall of adequate overseas repair facilities. *Horizon* places emphasis on technology to fill the hole left behind by a smaller crew and the absence of a mobile maintenance platforms, such as tenders, but the proposed technologies must be examined carefully or the readiness of the U.S. Navy could suffer.

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I. INTRODUCTION

A. RESEARCH GOALS

The purpose of this thesis is to produce a simulation tool to gain insight into the possible maintenance requirements for a single ship deployed for a period of three years. By performing sensitivity analysis on the input parameters of the simulation, trends can be represented graphically which will allow the user to identify the most critical characteristics of a surface ship during a three-year deployment. The simulation will also provide an indication of the amount of overseas maintenance support which might be required for this length of deployment.

This study provides an overview of possible surface ship maintenance and repair requirements for deployed units. Justification for deployed repair assets, and flexibility in overseas maintenance and repair contracting, is addressed. The study is not specific to any one area of operation or ship deployment region. The model is run with no specific logistic support structure in order to gain insight into the demands created from the ship and not any other outside repair requirements.

B. BACKGROUND

The United States Navy deploys its forces overseas to support the National Security Strategy core objectives. In the words of the Chief of Naval Operations (CNO), Admiral Johnson, "naval forces will use forward deployed presence to achieve the National Military Strategy objectives of promoting regional stability and defeating adversaries. Forward deployed presence is the way naval forces shape the environment

and respond to crises." [Ref. 1] In addition, the decrease in numbers of United States military bases overseas has placed an even greater emphasis on the importance of forward deployed naval forces. The Navy's long-range planning objectives, as put forth by the CNO, are to "procure sufficient ships and aircraft, with balanced readiness, manpower support, and maintenance, to support the national strategic requirements for assured crisis response and warfighting." [Ref. 1] With the reductions in military budgets, manpower, and infrastructure, the U.S. Navy must "implement policies, training and maintenance strategies, and technologies that will provide the capability for a larger fraction of the fleet to be forward deployed by permitting future ships to be manned with significantly reduced crew sizes, and by permitting rotation of crews to ships that are forward-deployed for extended periods." [Ref. 1]

With the task of reducing crew sizes and maintaining forward-deployed ships for extended periods comes several significant challenges. The quality of the crew member must be improved in order to meet the additional tasks and responsibilities associated with being the operator and the maintainer of complicated equipment. Training methods must be moved in the direction of virtual reality and simulations that are cost effective but "real" enough to be worth-while learning aids. Ship and aircraft systems must be able to perform "self-assessment of maintenance requirements, to operate for extended deployments without routine outside maintenance, and to require less depot-level maintenance over their service lives." [Ref. 1] Maintenance requirements consume the largest number of man-hours in any community in the U.S. Navy, and the reduction of this demand is the key element in successfully reducing manpower without sacrificing

readiness. Lastly, in order to offset material investment costs, the Navy must "reduce the size and cost of the logistic support structure through aggressive reduction of logistic response time, through prudent integrated logistic support and reliability investments, and through improved asset visibility with the use of information technology." [Ref. 1]

In June 1997, the Chief of Naval Operations Strategic Studies Group (SSG) XVI published a new surface ship deployment concept, known as *Horizon*, that addresses many of the challenges of deploying ships for extended periods and rotating crews. In addition, the Sustainment Concept Generation Team of SSG XVI researched improvements in maintenance practices that must be accomplished in order to maintain surface ships with reduced crews. The Vice Chief of Naval Operations, Admiral Pilling, stated that "because of its significant potential, I want to ensure that *Horizon* is carefully scrutinized to determine which, if any, of its features should be implemented." [Ref. 2] Questions such as

- What is the required minimum system performance?
- What features and capabilities must the overseas logistics support structure have to sustain vessels overseas for an extended period?

must be addressed.

C. *HORIZON* CONCEPT

The Chief of Naval Operations Strategic Studies Group XV met in November of 1995. The results of its study of naval ship sustainment warned of a reduction of foreign basing and the impact on deployed U.S. vessels. The study made several recommendations.

- Every ship a combatant with more time on station.

- Less dependency on overseas basing.
- Reduction of manpower.
- Reduction in time from supply source to end-user.

These recommendations were then further examined by SSG XVI and the *Horizon* concept.

In June of 1997, the *Horizon* Concept Generation Team of SSG XVI introduced the "Future Force Operation Plan". Within this innovative plan, the gap between the decreasing size and shape of the Navy's structure and the increasing requirement for forward presence in support of the National Security Strategy is bridged by deploying combat ships for periods of up to three years. The *Horizon* concept encompasses the four key elements listed below.

- Ships will be capable of remaining forward-deployed for up to three years.
- Fully trained and ready Sailors will rotate to the forward deployed platforms.
- Operationally and professionally focused shore billets will make 80% of our people available for deployment in Operational Duty status.
- A new organizational structure, centered in fleet concentration areas, will train, maintain, and operate the force.

The *Horizon* concept presents a "revolutionary operational approach that will provide continual naval presence in all theaters, a robust crisis response and surge capability, and a mechanism for collapsing the shore infrastructure." [Ref. 3] However, one of the limiting factors in the execution of this concept is the frequency of shore-based maintenance required for unscheduled ship-system failures during the deployment period.

The objectives of maintaining a continuous presence overseas and quickly responding to crises will not be met if the vessels are in need of outside assistance too often or for too long a period. The Sustainment Concept Generation Team of SSG XVI specifically addresses the challenges of sustainment and maintenance with four key elements: Logistics Process, Maintenance Plan, Netted Small Smart Sensors, and the Logistics Network.

1. Logistics Process

The logistics process of sustainment encompasses five functional areas: Supply, Transportation, Engineering, Health Services, and Maintenance. [Ref. 3] The SSG study focused on the area of Maintenance because it is such a "large portion of the decreasing budget, and industry has introduced promising maintenance technologies which reduce personnel requirements, reduce maintenance costs, and keep units at sea for longer periods of time." [Ref. 3] The study sites examples of commercial corporations that keep ships stationed overseas for more than 20 years and require only one month in depot maintenance in CONUS for every two years of operation.

2. Maintenance Plan

Equipment will always require maintenance to correct and prevent failures. The Navy currently uses a Planned Maintenance System (PMS) that requires certain checks, parts replacement, etc. to be performed at fixed intervals of time. This system is highly intensive in manpower and may encompass tasks that are not required. Alternatives to a regularly scheduled maintenance system are a Conditioned-Based Maintenance (CBM)

or a Cognitive-Based Maintenance (CogBM) system of scheduling maintenance. CBM techniques enable a technician to examine system output to determine the machinery health and any required maintenance. However, CBM is limited by the diagnostic capability of the technician. One step further is CogBM which monitors the sensor data and automatically pushes the preventive or corrective maintenance actions to the technician. CogBM is not limited by the diagnostic capability of the technician. These commercial techniques are being explored by the Navy as stated by the Sustainment Concept Generation Team of SSG XVI.

3. Netted Small Smart Sensors

Sensor technology is the cornerstone of CogBM. Small netted smart sensors would be used to monitor ambient space conditions and specific equipment operation. Spaces and equipment could then be monitored remotely by a smaller number of personnel. The smaller crew would be able to perform maintenance on a conditional basis rather than a periodic one. By only doing maintenance when maintenance is required, there is a potential reduction in maintenance dollars and maintenance man-hours. Smart sensors increase the diagnostic support for the equipment on a ship. Intrinsic values such as vibration, noise, temperature, load and normal functional data also could be monitored externally by shore-based technicians and diagnostic equipment that could anticipate pending equipment malfunction. Additionally, netted small smart sensor technology could be designed to order parts automatically for an anticipated failure before the failure actually happens. This would tend to shrink logistic delays and could eliminate collateral damage that accompanies such failures. Questions about the reliability and the parts

support, in cases of failure, of these sensors would need to be addressed.

4. Logistics Network

With a reduction in crew size, there could be a reduction in the overall expertise resident in the ship. A Logistics Network (LOGNET) would connect the ship's crew with technical experts, such as the In-Service Engineering Agent (ISEA) and the Original Equipment Manufacturer (OEM). All machinery or system information is netted and passed off the ship to the LOGNET. Information could then be pulled off the net by authorized users on an as-needed basis. LOGNET would produce a reduction in the ashore military maintenance personnel required to sustain a ship at sea. The support would come from civilian technical experts. The crew could receive its technical assistance directly from the ISEA or OEM. In addition, data could automatically be collected on system performance Navy-wide that could indicate the need for any design corrections to the equipment. There would be many benefits from direct connectivity to the fleet's maintenance community especially from ships deployed in remote areas of the world.

The Sustainment Generation Team of SSG XVI presented these concepts as necessary capabilities to support the plans for future surface ship operations and the *Horizon* concept. *Horizon* places the emphasis on technology to fill the hole left behind by a smaller crew, but these technologies must be examined carefully or the readiness of the U.S. Navy could suffer.

D. DEPLOYED MAINTENANCE

Deploying ships overseas for extended periods places a great emphasis on the

structure and capability of maintenance support facilities. Maintenance can be classified into two areas: *organic* and *inorganic* maintenance. *Organic* maintenance is performed by the personnel on the ship or the personnel from ships in its battlegroup. A ship does not necessarily have to leave station in order to complete *organic* maintenance. *Inorganic* maintenance is performed by a non-resident industrial facility, or with equipment, or special expertise, that is not resident on the ship or within its battlegroup. A ship will have to leave station in order to complete *inorganic* maintenance. A ship's ability to complete maintenance or repairs *organically* depends upon the technical expertise, availability of diagnostic equipment and repair parts, and the types of repair equipment resident on the ship or ships in its company. Any repairs outside the capability of these assets is considered *inorganic*.

In the past, overseas maintenance managers had two basic industrial bases from which to draw support for *inorganic* maintenance: shore-based industrial facilities and mobile maintenance vessels. Mobile maintenance vessels, or ship tenders, have repair equipment, technical expertise, and repair parts to assist in the repair of ships in a region. The key to these ships is their mobility. However, ship tenders have been removed from the inventory, with no plans for replacement. This places much of the maintenance requirements for overseas maintenance on shore-based industrial facilities.

Guidance and policy direction for deployed maintenance for the Navy is governed by CINCLANTFLT/CINCPACFLTINST 4790.3 CH-1, the Joint Fleet Maintenance Manual. Responsibility for deployed ship maintenance is broken up into three Areas of Responsibility (AOR), as listed below.

- Commander in Chief, United States Naval Force, Europe (CINCUSNAVEUR)
- Commander, Fifth Fleet (COMFIFTHFLT)
- Commander, Seventh Fleet (COMSEVENTHFLT)

Surface ship maintenance for deployed ships is provided based on the following priorities: [Ref. 4]

- *Emergent repairs* involving major equipment failures.
- *Emergent repairs* involving minor equipment failures.
- Planned maintenance availabilities.
- Continuous Ship-to-Shop availabilities.
- Periodic inspection requirements.

Emergent repairs, conducted in remote locations away from industrial facilities to correct failures, are accomplished by the use of repair Fly-Away-Teams (FATs) or Tiger Teams from a shore-based repair activity. These teams are transported to the affected unit by surface craft or helicopter, and provide skills, equipment and technical expertise necessary to augment ship's force in correcting the casualty.

In addition to local or in-theater repair teams, technical assistance teams from CONUS can be used for high interest and major casualty repairs. The use of CONUS teams is far more expensive compared to local teams and is normally viewed by responsible maintenance managers as a final and last resort for this reason.

A surface ship deployed for an extended period may demand more maintenance requirements because of the age of the systems on board. Also, a reduction in ship's

company implies a reduction in resident technical expertise. The loss of expertise will need to be augmented by shore-based repair facilities. Current shore-based maintenance facilities overseas may not be able to handle all of the demands for the necessary maintenance support required by deployed combat vessels.

Shore-based maintenance must be accomplished by military members, or else be contracted out. Military maintenance personnel may be preferred because they are familiar with military maintenance standards and the equipment. Ship surveyors are required to manage surface ship maintenance availabilities by contractors to ensure maintenance standards are upheld. In addition, section 7309C of Title 10, United States Code, prohibits ships homeported in the United States from being overhauled, repaired, or maintained overseas except for emergent repairs. The need for more overseas military repair facilities and capability could become crucial if material readiness of deployed ships is to be maintained in remote areas.

As a point of illustration, in 1991 three combat vessels were assigned to patrol duties in the Red Sea when the last aircraft carrier battle group departed. The three ships had little onboard industrial repair capability and were mostly powered by single propulsion plants. Operational requirements also dictated that these units remain close to the North Red Sea. Local commercial contractor support was not available. A co-operative maintenance plan had to be developed between two fleet commanders that exchanged deployed units into the region in order to perform maintenance on a rotational basis. Strategic positioning of military maintenance facilities with significant fly-away technical support is essential in cases such as this.

II. DEPLOYED CORRECTIVE MAINTENANCE MODEL

A. GENERAL

The conceptual model used in this thesis represents the corrective maintenance requirements and material readiness for a ship deployed for a period of three years, from an optimistic, best-case point of view. The model does not examine the interactions of multiple platforms operating in the same region, although it could be expanded to allow for these easily. The model is broken down into three main elements: a ship, a system, and a system's failure modes.

1. Ships

The ship in the model holds the systems which are examined. The ship is required to have three types of systems represented: a *propulsion* system, a *navigation* system, and a *combat* system. Additional systems can be added to the ship, but these basic systems must be present. The ship must be able to evaluate its equipment readiness rating, based upon the requirements defined in Naval Warfare Publication (NWP) 1-03.3 (REV. A). When a system is no longer able to operate as a consequence of failures, the ship must reevaluate its equipment readiness rating.

When a failure occurs that requires *inorganic* support, the ship will leave station and travel to a base to be repaired. The ship does not leave base until all *inorganic* repairs are complete. The ship keeps track of the length of continuous on-station and off-station times as the deployment goes on. On-station time begins when the ship first arrives at its station and ends when the ship is required to leave station. Off-station time

begins when the ship is required to leave station and ends when the ship arrives back on-station. Operational availability (A_o) can be assessed for the ship based on expression (2.1).

$$A_o = \textit{Mean On-Station Time} / (\textit{Mean On-Station Time} + \textit{Mean Off-Station Time}) \qquad \textbf{(2.1)}$$

Note that the above is a theoretical measure of effectiveness that could be estimated from historical operational data, or predicted using mathematical models or simulation.

2. Systems

A system in the model is defined as a complete and independent component of the ship that contributes to the overall readiness of the ship. The model considers three key systems: the *propulsion* system, the *navigation* system, and the *combat* system. Each of these systems can be represented as a single piece of equipment, or as multiple pieces of equipment or sub-systems in parallel. Each system has one, or multiple failure modes associated with it. The failure modes are assumed to be independent, and with not necessarily identically distributed times to failure. Each system has an on-cycle and off-cycle which describe how long the system is on and off respectively.

When a system is turned on, all of its associated failure modes are activated. If a failure occurs, the system will automatically turn off, and the ship is notified that the system is down until repairs are made.

3. Failure Modes

Activation of a failure mode represents a complete failure of the system. A

failure mode has several characteristics associated with it.

- Time-to-failure distribution, or failure-generating process model.
- Probability of *organic* repair.
- Logistics delay-time distribution.
- Repair delay-time distribution.

When a failure occurs, the associated system is *notified.* The type of repair is based upon the probability of *organic* repair. *Organic* repair capability is based upon the complexity of the system and failure, the amount of technical expertise resident on the ship, the industrial repair capability resident on the ship, and the availability of diagnostic equipment and repair parts. If the failure is characterized as requiring *inorganic* support, the ship must leave station to complete the repair.

Each failure mode is responsible for keeping track of its own repair. It has a random time-delay associated with the logistics required to repair the failure. This delay incorporates the time to identify, order and receive any parts required. This delay also includes any technical support that the ship's crew may need to diagnose the casualty. After the logistics delay is complete, the failure is ready to be repaired. The failure mode has a random time of repair. Once the repair is complete, the system is operational again with respect to the repaired failure mode.

The conceptual model is made up of one ship on deployment in a non-specific area of operation or deployment region. The particular geographic region, relation to foreign ports, etc. could be made specific if desired. The ship has a propulsion system consisting of four identical engines powering two shafts (i.e. two engines on one shaft).

Only one engine is required to power a shaft; the other engine on the shaft is in *cold standby*. When equipment is in *cold standby*, its respective failure modes are not *active*. When equipment is started, it is subject to start-up failures based on a fixed probability of a successful start-up. In the future, this probability of a successful start-up could be a function of time. The ship has a navigation system consisting of two identical navigation radar. One radar is designated as the primary radar and is always operating if it is not failed. The other radar is in *cold standby* and used only if the primary is failed. The ship has a combat system represented by one fire control radar. The fire control radar is operated only a fraction of time during the day for testing. This model does not consider any increased equipment operations during combat or crisis response. The ship is to be operated for a continuous three year deployment. In practice, these sub-systems are augmented by other sub-systems, such as communications, weapons, and power generation.

B. MODEL INPUTS

The inputs of the model and a brief description are as follows:

Ship Name – This input is the name or designation of the ship. For a single ship exercise, this input is not used. However, for multi-ship exercises, this input is used to differentiate one ship from another.

Number of Ship Mission Areas/ Mission Area Names – This input is the number and names of the mission areas that the ship is responsible for when on-station. The mission areas are defined by the types of systems, or sub-systems, the ship has onboard. Each system, or sub-system, contributes to a specific list of mission areas of the

ship. For example, a *propulsion* system contributes to the ship's mission of mobility. NWP 1-03.3 (REV. A) illustrates how to calculate the mission area rating based upon equipment status criteria per mission area. The mission rating values and the associated percent of "major end items of equipment possessed and combat ready" within a specific mission area are shown below in Table 1.

Mission Rating	Percent of major end items of equipment possessed and combat ready within Mission Area
M-1	$\geq 90\%$
M-2	$\geq 70\%$
M-3	$\geq 60\%$
M-4	$< 60\%$

Table 1: Equipment Status Resource Criteria

Transit Delay (in hours) – This input represents the typical (mean) time it takes the ship to transit to station from its base. This is also the time it takes for the ship to return to base from its station. In practice these times may vary because of the weather or threat. The length or difficulty of the transit may influence failures of ship systems. This variability is not modeled.

Number of Engines for Propulsion – This input is the number of engines, E, for the *propulsion* system, one of the three required systems for the ship. The number of engines must be greater than zero. If the number of engines is one or two, a single-shaft *propulsion* system is used. If the number of engines is more than two, a dual-shaft *propulsion* system is used.

Number of Navigation Components – This input is the number, N, of

independent ship navigation radar components. The navigation system is a parallel system with N redundant radars. When one radar is online, the others are on cold standby. The failures of this system is not dependent upon the availability of the ship's power.

Number of Combat System Components - This input is the number, C, of independent ship fire control radar components. The combat system is a parallel system with C redundant fire control radars. When one radar is online, the others are on cold standby. Other combat systems can be entered under a miscellaneous category as long as they are independent systems. The failures of this system is not dependent upon the availability of the ship's power.

Number of Miscellaneous Systems – This input is the number, M, of independent miscellaneous systems onboard the ship. These systems operate according to their respective on and off cycle times, but do not have backup systems to operate if they fail.

System Name/ System Type – This input is the name or designation of the system and the system type. The name allows the user to differentiate system performance. The type of system is either engine, navigation, combat, or miscellaneous.

Number /Name(s) of System Mission Areas – This input is the number and name of the ship mission areas affected by a system failure or repair. This characteristic of each system allows the ship to calculate an equipment mission area rating for each mission area. The equipment mission area rating is based upon the percent of operational equipment in each mission area as shown in Table 1.

System On Cycle (in hours) – This input is the length of time in hours that the system operates when it is turned on. If a failure occurs when the system is operating during its on cycle, the system is automatically turned off.

System Off Cycle (in hours) – This input is the length of time in hours that the system is inactive when it is turned off. A failure cannot occur during the system's off cycle.

System Start-Up Success Probability – This input is the probability that the system will successfully start. The probability does not vary with the age of the system, but an age-dependent start-up success probability should be considered for future modeling. If a system does not start, it is treated as a failure and must be repaired before operation.

Number of Failure Modes for the System – This input is the number of failure modes to be read in from the input file for a given system. The failure modes are assumed to be independent from each other, and only affect the assigned system.

Failure Mode Name – This input is the name of the failure mode. It is used to identify which failure mode is active when a failure occurs.

Failure Mode Distribution/ Parameters – This input is the distribution and its associated parameters for the random time to failure for a system's failure mode. The failures in this model are categorized by the Navy's criteria in NWP 1-03.3 (REV. A). The categories and their respective criteria are listed in Table 2. These failures result in some degree of degradation to the ship's primary mission areas.

Initially, a time to failure, *T*, is generated for each failure mode. As the system is

operated, actual hours of operation are added up. When the hours of operation are equal to the time to failure, T, that failure mode is activated, and the system fails. Once the failure mode has been activated, a new time to failure is generated with the specified distribution.

Casualty Category	Equipment Criteria
C-2	A deficiency exists in mission-essential equipment which cause a minor degradation in any primary mission
C-3	A deficiency exists in mission-essential equipment which causes a major degradation but not the loss of a primary mission
C-4	A deficiency exists in mission-essential equipment that is worse than category 3 and causes a loss of a primary mission.

Table 2: Casualty Categories and Criteria

Logistics Delay Distribution/ Parameters – This input is the distribution, and its parameters, that represent the random logistics delay for a failure mode. Each failure mode has its own logistics delay. The delay represents the random time associated with troubleshooting the failure, identifying parts, and receiving those parts from the ship's inventory or from an outside source. Once a failure has occurred, a random logistics delay is generated with respect to the distribution. Repairs cannot begin until the logistics delay is complete.

Repair Delay Distribution/ Parameters – This input is the distribution, and its parameters, that represent the random repair delay for a failure mode. Each failure mode

has its own repair delay. The delay represents the random time associated with the repair and operational testing of a failed system. Once the logistics delay is complete, the repair delay is generated. All repairs are complete repairs; the system is fully operational with respect to any repaired failure mode.

Probability of *Organic* Repair – This input is the probability that the failure is repairable with *organic* assets. Each failure mode has its own *organic* repair probability. If a simulated failure is found to be an *organic* repair, the ship is not required to leave station for repairs. The logistic delay is not dependent upon whether or not the repair is *organic*.

C. MODEL FLOW

The model centers around the performance of a ship during its three year deployment once it has entered the deployment area. The transit from CONUS to the area of responsibility (AOR) and returning to CONUS are time periods not considered by the model. The model is concerned with the failures that would cause a C-2, C-3 or C-4 casualty and with all associated repairs (refer to Table 2).

The model begins with the ship at base in the AOR with all systems fully operational. This is equal to a mission equipment readiness rating of M-1 (refer to Table 1). The ship is immediately sent to its station and experiences the transit delay. The ship operates its equipment according to the on and off cycles times until a failure occurs. A failure can occur during three basic states of the ship: the ship is in transit to its station, the ship is on-station, the ship is returning to base.

Once a failure occurs, the type of repair is decided with a random number draw.

If the repair is *organic*, a logistics delay is started. If the repair is *inorganic*, a logistics delay is started, and the ship is sent to base. The sub-system is considered off-line when one of its failure modes has occurred, and it can only be returned to operation after the repairs are made. The mission area rating of the ship affected by the sub-system failure is degraded.

After the logistics delay is complete, the repairs are ready to commence. If the repair is classified as *organic*, the repair can start immediately and is finished after the repair delay is complete. If the repair is classified as *inorganic*, the repair can only begin when the ship has returned to base, after the transit delay, and the logistics delay is complete. The transit time to/from base contributes to the ship's off-station time.

After the repair delay is complete, the system is assumed to be as good as new. There are no partial repairs represented in the model. This allows the model to present an optimistic, best-case view of the number of failures and the required outside repair support during a three year deployment. After repair, the system is in an operationally ready status. The ship's mission area equipment rating affected by the system repair is then upgraded . If the repair is an *inorganic* repair, the ship is able to return to station if and only if there are no other inorganic repairs in its queue. The system is turned on again by the ship according to the system's on and off cycles.

D. MODEL ASSUMPTIONS

This model uses several assumptions in order to simplify the analysis. The following is a list of the key assumptions.

- Only *inorganic* repairs force the ship to leave station.
- All failure modes are independent (no accounting for power-loss failures

common to several systems).

- Distribution parameters do not change with time (does not represent age effects or wear).
- All repairs are good-as-new.
- Repairs can be accomplished in parallel.
- *Inorganic* repairs can only be accomplished at base.
- Ships do not leave base with uncorrected *inorganic* repairs.
- The base is always immediately available for repair work.
- Transit delays to/ from station/ base are constant.

These assumptions used are simplifications that present an optimistic best-case view of deployed maintenance during a three-year deployment. The number of occurrences of base repair for a single ship under these assumptions allows a maintenance manager to have some insight into the amount of repair capability required without losing relevancy.

E. MEASURES OF EFFECTIVENESS

There are several measures of effectiveness (MOE) for this model to evaluate the performance of a ship during a three-year deployment. The MOE's used in this analysis are listed below.

Mean On-Station Time (in hours) – This MOE is the mean of the continuous on-station times for the ship during a three year deployment. It estimates the expected time a ship remains on-station until a failure causes it to return to base. The standard deviation of the continuous on-station times is also estimated.

Mean Off-Station Time (in hours) – This MOE is the mean of the continuous off-station times for the ship during a three-year deployment. It estimates the expected time a ship remains off-station for the repair of a total system failure. The standard deviation of the continuous off-station times is also estimated.

Mean Time Between Base Repair (MTBBR) (in hours) – This MOE is mean time between the occurrence of a base repair. The standard deviation of the times between the occurrence of a base repair is also estimated.

Estimated Operational Availability (A_o) – This MOE is the long-run percentage of time that the ship is able to be on-station. It is estimated by the ratio of the estimated mean on-station time to the sum of the estimated mean on-station time and the estimated mean off-station time (see Equation 2.1). This MOE is an attempt at estimating the probability that the ship is on-station when a random and unpredictable crisis occurs. One must be careful in using this MOE because it can be misleading. If a ship has a relatively short mean downtime as compared with its mean uptime, the estimated A_o will be high, but the high A_o value might be hiding a small uptime value. For example, if the mean uptime is 100 hours and the mean down time is 1 hour, the estimated A_o will be .99, but a mean uptime of 100 hours for a ship is not very good. Also, this estimate of A_o does not reflect the probability that the ship will be able to *respond* to the crisis with all systems available. The latter is an interesting question for extended deployments, but is not addressed in this thesis.

These MOE's are compiled over the entire three-year deployment, and do not offer any insight into the variability of their values for any interim time periods.

However, the model could be run for any desired time length independently. Repeated simulations of three-year deployments show the variability of these estimated MOE's.

III. METHODOLOGY

A. GENERAL

An object-oriented, discrete-event, Monte Carlo simulation written in Java is used as the analytical tool for the extended deployment model. The simulation mimics the occurrence of system failures on a ship and follows the action required to repair the casualty. With a simulation, it is possible to manipulate the model in order to experiment with alternative operating conditions for the ship. The simulation is used to investigate the sensitivity of the model to several of the inputs.

The simulation has three main object types: the ship, the systems, and the failure modes. All three objects can be created from input files independently or from a single input file. The objects used in this thesis were created from a single input file. For each simulation run, a ship with the characteristics given in the input file is created and started out on a three-year deployment. The ship experiences random failures, transit delays, logistics delays, and repair delays as described by the model. The ship object collects the on-station times and off-station times experienced by the ship during the three years. At the end of the simulation run, the estimated means and standard deviations for the measures of effectiveness are based upon the observed on-station and off-station times of the ship throughout the entire three-year deployment. Successive runs are given different random number seeds to generate independent results. The simulation is run for ten independent three-year deployments. The mean and standard error of the means for each measure are calculated. The number of simulated deployments results in a standard error of less than five percent of the mean for each measure.

The output of the simulation is written to a text file which can be imported into a spreadsheet for further analysis. In this thesis, Microsoft Excel software is used for output analysis.

B. SIMULATION INPUT

The input for the simulation is a formatted text file representing all the data necessary to create the desired ship profile. An example of an input file is shown in Appendix A. The inputs to the simulation are required to be in the order specified and are delimited with a slant (i.e. "/"). Comments in the input file are preceded by a pound sign (i.e. #) at the beginning of the line; the entire line is ignored by the simulation. The order and specifics of the simulation inputs are listed below.

Ship Name – The name or designation of the ship. This input is useful when handling more than one ship.

Ship Location – The location name of the ship. This input is used to track which area of responsibility a ship is operating. This input is necessary when handling more than one area of responsibility.

Number of Ship Mission Areas – The number of ship mission areas represented by the systems onboard.

Ship Mission Areas – The name(s) or abbreviations for the ship mission areas (in no particular order). The number of mission areas listed must match the previous input. The list of mission areas here must match the mission areas listed for each ship system.

Transit Delay (in hours) – The mean transit delay (in hours) for the ship to move from base to station or from station to base. The variability of this transit time currently

is not modeled but this feature could be added in the future.

These next inputs are required for each category of system (i.e. engine, navigation, combat system, or miscellaneous system) and must be repeated in the input file for as many times as the Number input states. The order of system input is Engine, Navigation, Combat, and Miscellaneous respectively.

Number of Eng/Nav/Combat/Misc Systems – The number of like engine, navigation, combat, miscellaneous systems on the ship.

System Name – The name or designation of the system. This input allows the user to differentiate one system from the other by name.

System Type – The type of system must be ENGINE for an engine system, NAVIGATION for a navigation system, COMBAT for a combat system, or MISC for a miscellaneous system.

Number of System Mission Areas – The number of system mission areas.

System Mission Areas – The name(s) of the mission area(s) that are affected when the system fails or is repaired. There must be as many mission areas listed here as required by the previous input. This input must match at least one of the Ship Mission Area's input.

System On-Cycle (in hours) – The continuous time the system is operated when it is turned on. After the on-cycle time is elapsed, the system is turned off, if a failure has not already occurred. A user input of less than zero indicates that the system is always operating when the ship is underway.

System Off-Cycle (in hours) – The continuous time the system is off. After the

off-cycle time is elapsed, the system is turned on, if it is operational. If the on-cycle input is less than zero, the off-cycle input must be less than zero to indicate that the system is always operating when the ship is underway.

System Start Survival – The probability that the system will start without failure when required.

System Number of Failure Modes – The number of failure modes for the system.

These next inputs are required for each failure mode and must be repeated in the input file for as many times as the Number of Failure Modes input states for each system.

Failure Mode Name – The name or designation of the failure mode. This input allows the user to differentiate one failure mode from another if the system has more than one failure mode.

Time to Failure Distribution/Parameters – The name of the distribution, the number of parameters, and the associated parameters for the distribution of the time to failure. The list of supported distributions are shown in Table 3. [Ref. 4]

Distribution	Distribution Input Name	Input Parameters
Exponential	EXPONENTIAL	Mean
Uniform	UNIFORM	Endpoints (a, b)
Erlang	ERLANG	Shape, Scale (n, β)
Gamma	GAMMA	Shape, Scale (α, β)
LogNormal	LOGNORMAL	Shape, Scale (μ, σ)
Weibull	WEIBULL	Shape, Scale (α, β)

Table 3: Supported Distributions and their simulation inputs.

Logistics Delay Distribution/Parameters – The name of the distribution, the

number of parameters, and the associated parameters for the distribution of the logistics delay of the failure mode. Refer to Table 3 for supported distributions.

Repair Delay Distribution/Parameters – The name of the distribution, the number of parameters, and the associated parameters for the distribution of the repair delay of the failure mode. Refer to Table 3 for supported distributions.

Probability of Organic Repair – The probability that a random failure from this failure mode will be repaired *organically*.

C. SIMULATION EVENTS

The simulation incorporates three main Java classes that schedule and run the events for the model. The three main Java classes are listed below.

- FailureMode
- SystemClass
- Vessel

The class names are spelled in the Java syntax for classes. Each class has its own events that it is responsible for scheduling, canceling and doing. The events listed for each class are spelled in the Java syntax for methods.

1. FailureMode

The class FailureMode contains the events FailureArrival, LogisticsArrival, and RepairArrival. Also within this class, the time-to-failure delay, logistics delay, and repair delay are generated. The failure delay is stopped and restarted every time its associated system is turned off and on respectively. The following is a brief description of each FailureMode event.

FailureArrival – This event happens when the time-to-failure delay is zero. A new random time-to-failure, T, is generated and saved for the next time-to-failure of the failure mode. A random logistics delay is generated and the LogisticsArrival event is scheduled. The level of repair also is generated based upon the probability of *organic* repair for the FailureMode. A random number is drawn and compared with the probability of *organic* repair input for the failure mode. If the random number is greater than the probability of *organic* repair, the level of repair is set to be *inorganic*. Lastly, the system that the failure affects is *informed* that a casualty has occurred.

LogisticsArrival – This event happens when the logistics delay is complete. A random repair delay is generated and the RepairArrival event is scheduled.

RepairArrival – This event happens when the repair delay is complete. The system that the failure affects is *informed* that the casualty is repaired.

2. SystemClass

The class SystemClass contains the events TurnSystemOn, and TurnSystemOff. Also within this class, all system failures and repairs are *processed*. When a system failure occurs, the system turns itself off and *informs* the vessel, or ship, that the system is failed. Likewise, when a system is repaired, the system is operational again, but is not immediately turned back on. The system is either turned on by the vessel, or it is turned on when its *off*-cycle time is complete. Also, the vessel is *informed* that the system is repaired.

The following is a brief description of each SystemClass event.

TurnSystemOn – This event happens when the system is scheduled to be turned

on. All required systems are initially turned on when the vessel, or ship, is getting underway. Other systems are turned on when its on-cycle, and off-cycle dictates. When a system is turned on, it is tested to see if the system survives the start based upon the start-up success probability input. If a the system has a successful start, all system failure modes schedule a failure based upon the remaining life of the time-to-failure delay. As a system is operated, the time-to-failure remaining life decreases. When a failure mode's time-to-failure remaining life is zero, a failure occurs.

TurnSystemOff – This event happens when a system is scheduled to be turned off, or a failure occurs. When the system is turned off, all failure modes save their remaining life until the system is turned on again. A failure cannot occur when the system is turned off, but it can fail to turn on successfully upon the next TurnSystemOn event.

3. Vessel

The Vessel class contains the events LeaveBase, VesselOnStation, LeaveStation, VesselAtBase, EngineShift, NavShift, CombatShift, StopDeployment. Also within this class, all system failures and repairs are *processed* with respect to the vessel. When a system failure occurs, the vessel's mission area ratings affected by the failure are degraded (see Table 1). Likewise, when a system is repaired, the system is operational again, and the vessel's mission area ratings affected by the repair are upgraded. The vessel also collects the off-station and on-station times. The statistics for these observations are summarized in the simulation output. The following is a brief description of each Vessel event.

LeaveBase – This event happens when the simulation is initially run and after all base repairs are complete. This event turns on all the required systems. The required systems are listed below.

- One engine per shaft.
- The primary navigation system.
- The primary combat system.
- All miscellaneous systems.

The event VesselOnStation is scheduled after a constant transit delay. The transit delay is in hours, and is input by the user. If the vessel experiences a failure that requires *inorganic* repair after the LeaveBase event and before the transit delay is complete, the VesselAtBase event is scheduled after one-half the transit delay.

VesselOnStation – This event happens after the transit delay is complete. This event triggers the start of the vessel's on-station time and the end of the vessel's off-station time.

LeaveStation – This event happens when the vessel experiences a failure that requires one or more *inorganic* repairs. This event triggers the start of one of the vessel's off-station times and the end of the vessel's current on-station time. This event schedules the VesselAtBase event after the constant transit delay.

VesselAtBase – This event happens after the transit delay from the LeaveStation event or after one-half the transit delay from a failure event (see LeaveBase event above). This event turns off all systems and triggers the availability of *inorganic* repairs to begin. When the logistics delay is complete and the VesselAtBase event has happened,

inorganic repairs can commence. *Inorganic* repairs are completed after the random repair delay generated from the FailureMode.

EngineShift – This event happens whenever any of the engines is turned on or off for a LeaveBase event, VesselAtBase event, or an engine failure. This event keeps track of which engines are scheduled to be turned on and which engines are scheduled to be turned off. If a vessel has one or two engines, it is assumed that the vessel has only one shaft for propulsion. If a vessel has more than two engines, it is assumed that the vessel has two shafts for propulsion. A shaft with two engines will alternate engines given the on-cycle and off-cycle. If a shaft with two engines has one engine failed, the remaining engine will stay online until the alternate engine is repaired. If the remaining engine fails, the shaft is offline. If three engines are failed at the same time, the ship is returned to base regardless of the types of repair required. If the engines are down for *organic* repairs, and the repairs are completed before the transit delay, the ship is returned to station.

NavShift – This event happens whenever any of the *navigation* systems is turned on or off for a LeaveBase event, VesselAtBase event, or a navigation failure. The TurnSystemOn and TurnSystemOff events are performed when a *navigation* system is turned on or off respectively. This event keeps track of the primary *navigation* system and the secondary systems. If a vessel has one *navigation* system, it is designated as primary. Any additional *navigation* systems are designated as alternate. The alternate *navigation* systems are placed on cold standby if the primary *navigation* system is operational. When the primary *navigation* system fails, the alternate *navigation* system is

turned on. When the primary *navigation* system is repaired, the primary *navigation* system is turned on, and the alternate *navigation* system is returned to cold standby.

CombatShift – This event is exactly like the NavShift event except that it applies to the *combat* systems.

StopDeployment – This event happens when the length of deployment is complete. If the vessel is on-station, it is returned to base. Once the vessel is at its base, the simulation is terminated. All output files are closed.

D. SIMULATION OUTPUT

The simulation program collects observations throughout the run that are used to evaluate the measures of the model. The primary observations are the continuous vessel up-times and vessel down-times. When the vessel is created, it requires three arguments. The first argument is the name of the input file. The second and third are the names of the output files for the vessel down times and vessel up times respectively. As the vessel experiences the completion of a continuous up time, that length of time is written to the *up-time* file. Likewise, as the vessel experiences the completion of a continuous down time, that length of time is written to the *down-time* file. The files are closed with the StopDeployment event.

These lengths of time are collected in a variable within the simulation that automatically estimates the mean and standard deviation of the observations. When a simulation run is complete, the following statistics are written to the screen.

- Mean Down-Time for the Vessel.
- Mean Up-Time for the Vessel.

- Mean Time Between Base Repair.

- Estimated Operational Availability (A_o).

With independent simulation runs using the same input file, the output of these simulation runs is collected. The mean and standard deviation of these observations is then estimated, allowing the user some insight into the mechanics of the model.

E. DATA

The data used to evaluate the model were obtained from Naval Sea Systems Command (NAVSEA). The data are single point estimates of the following parameters: Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), and Mean Logistics Delay Time (MLDT), all in hours, for selected ship systems. The data represent the time-to-failure, logistics delay and repair delay for "major and critical" failures of the equipment. This corresponds to failures that keep the ship from having a readiness rating of M-1 or M-2 (see Table 1) and cause C3 and C4 casualty reports (see Table 2).

From the list of available systems, a few representative systems were selected as inputs into the model. Table 4 below lists the systems used in the model and the data associated with them. The decision to simulate a *propulsion* system, *navigation* system, and *combat* system alone is made to examine an optimistic best-case model.

System Name	MTBF (in hours)	MTTR (in hours)	MLDT (in hours)
Engines			
Gas Generator	61,000	48	210
Power Turbine	82,000	72	210
Accessories	400	30	210
Navigation Radar (SPS-64)	3000	1	300
Fire Control Radar (MK95 MOD1)	250	4	300

Table 4: System inputs and associated parameters.

Future model analysis should incorporate more systems as inputs in such a model and assess the effects of an alternative approach.

It is of special interest that the Engine Accessories and Fire Control Radar have relatively short times-to-failure, and possibly could dominate the *inorganic* repair requirements of the ship. Also, the relatively long logistics delays show that they could have a strong effect on the measures of the model, and that there is great room for improvement in this area.

F. SHIP PROFILE

The analysis of the extended surface ship deployment model is broken up into four case studies each using a base-case ship profile and manipulating selected model inputs independently to see the effects. The goal is to gain insight into which inputs to the model affect the model the most or the least, based upon the chosen measures of the model. The sensitivity of the model to its inputs is accomplished by manipulating the mean time between failure (MTBF), mean logistics delay time (MLDT), and percent of *organic* repair inputs for the *propulsion* system alone. The *propulsion* system is selected since it is common to all surface ships, and its demand for outside assistance is non-

trivial. The ship profile used for the model analysis consists of the following:

- Four engine systems propelling two shafts.
- Two identical navigation radars.
- One combat system radar.

These systems were chosen as a starting point for the analysis for an optimistic best-case model of the corrective maintenance requirements of an extended surface ship deployment.

1. Case 1

The first case study assumes that all time-to-failure distributions, repair delay distributions, and logistic delay distributions are exponential. For the time-to-failure, the exponential distribution represents a "no-wear" failure characteristic. "No-wear" is shown by a device that given it has survived to age *t,* then the conditional distribution for its remaining life is the same as if it were new. This is a logical point to begin the analysis since the data used are single point estimates of the mean, and the exponential distribution is conventionally used as the initial model in such circumstances. Within this case study, sensitivity analysis is performed on the MTBF, MLDT, and percent of *organic* repair for the *propulsion* system. Ten independent three-year deployments are simulated, and the measures of mean off-station time, mean on-station time, mean time between base repair (MTBBR), and operational availability (Ao) are estimated.

2. Case 2

The second case study replaces the exponential distribution for the times-to-

failure of the *propulsion* system with a "wear-out" distribution. The time-to-failure of a device follows a "wear-out" failure distribution if given it has survived to age t, then it has a smaller chance of surviving a mission, of any specified duration, than it would if it were new. The repair delay and logistic delay distributions for the *propulsion* system remain exponential. The characteristics for the navigation and combat systems are unchanged. This is the next logical step since most engineering equipment fails with "wear-out" characteristics. The Weibull distribution with a shape parameter greater than one is used to illustrate "wear-out" characteristics. A Weibull distribution with a shape parameter of 1.2 is chosen for this case. Stronger degrees of "wear-out" are modeled in Case 3. Like the Case 1 study, sensitivity analysis is performed on the MTBF, MLDT and percent of *organic* repair for the *propulsion* system. Ten independent three-year deployments are simulated, and the measures of mean off-station time, mean on-station time, mean time between base repair, and operational availability are estimated. The same initial random number seeds as in Case 1 are used.

3. Case 3

The third case study examines the sensitivity of the model to changes in the degree of "wear-out" failure characteristics of the *propulsion* system. This degree of "wear-out" is increased by increasing the shape parameter of the Weibull distribution greater than one. A Weibull distribution with a shape parameter of one is an exponential distribution, and represents "no-wear" failure characteristics. A shape parameter greater than one represents "wear-out" failure characteristics, and a shape parameter of less than one represents "near-birth" failure characteristics. Shape parameters from 0.8 to 2.0

increments are used in this case to model failure characteristics. Ten independent three-year deployments are simulated, and the measures of mean off-station time, mean on-station time, mean time between base repair, and operational availability are estimated for both "wear-out" and "near-birth" failure characteristics.

4. Case 4

The forth case study examines the sensitivity of the model to changes in the transit time of the ship from base to station (or from station to base). This study examines the effects of the relative distance between a shore repair facility and the station of the ship it is required to support. The initial analysis assumes that the transit delay between base and station is 24 hours. This delay is increased in increments of 24 hours up to a maximum of 144 hours to examine the sensitivity of the model to the input. Ten independent three-year deployments are simulated, and the measures of mean off-station time, mean on-station time, mean time between base repair, and operational availability are estimated.

IV. RESULTS AND ANALYSIS

As previously discussed, the analysis of the model is broken up into four cases. The first case, Case 1, assumes that all times-to-failure are exponentially distributed. Since the data used for the analysis are single estimates of the mean, this assumption is a logical place to start. The second case, Case 2, replaces the exponential time-to-failure distributions with a "wear-out" failure distribution. For this study, the Weibull distribution with a shape parameter of 1.2 is chosen to represent the "wear-out" failure characteristic. The third case, Case 3, expands on the second case by exploring the sensitivity of the model to the value of the shape parameter of the Weibull time-to-failure distribution. Even though the shape parameter changes, adjustments in the scale parameter of the Weibull distribution maintain the mean time to failure of each failure model. Failure distributions with increasing degrees of "wear-out" (shape > 1) along with "near-birth" (shape < 1) failure distributions are examined with shape parameters of 0.8 to 2.0. The last case, Case 4, examines the sensitivity of the model to the value of the transit delay between base and station. A longer transit delay models ships that might be deployed to remote areas with respect to the nearest shore-based repair facility.

In all of these cases, a base case is used to evaluate the sensitivity of the model to the input values. Note that the base case represents a ship with only a 50% capability of *organic* repair, which could be the case with a smaller, less capable crew. Also the simulation *automatically* sends a ship in to base for C-3/C-4 failures which is normally handled on a case-by-case basis. With these assumptions, the base case output will be low for mean on-station times and operational availability.

Within each case, the measures of mean off-station time, mean on-station time, mean time between base repair (MTBBR), and operational availability (A_o) are estimated. For a given ship profile, ten independent three-year deployments are simulated and the measures are estimated for each run. When an input is changed, the same ten independent runs are performed. The only variation in the measures of the model between same-numbered runs are due to changes in the input values of the model.

A. CASE 1: EXPONENTIAL FAILURE DISTRIBUTIONS

Since the data used to evaluate this model are given as estimates of the mean times to failure, the logical starting point for analysis is to use the exponential distribution to generate times to failure. The exponential distribution is conventionally used as a first model to describe times to failure and only requires a single parameter. With this assumption, sensitivity analysis is performed independently on three of the input parameters: mean time between failure (MTBF), mean logistics delay time (MLDT) and percent of *organic* repair. For each change of an input parameter, ten independent three-year deployments are simulated, and the values of mean off-station time, mean on-station time, MTBBR and A_o are estimated.

In order to perform sensitivity analysis, a base-case simulation output for which to compare subsequent changes in the model output is generated. The base-case ship profile for Case 1 is shown in Table 5 below. The inputs for MTBF, MLDT and percent of *organic* repair then are changed independently and the measures of the model are re-evaluated. The new values for the measures of the model are compared to the values of the measures in the base case. The output for Case 1 is shown in Appendix B.

From Table 5, there are four engines modeled. This indicates that the ship has two shafts for propulsion and two redundant engines per shaft. However, only one engine is required to be online per shaft at one time. Also note that failure mode 3, FM3, for the engines has the lowest MTBF and will dominate the required repairs of the ship.

System Name	Failure Mode	Failure Distribution	MTBF (hrs)	Logistics Distribution	MLDT (hrs)	Repair Distribution	MTTR (hrs)	Percent of *Organic* Repair
Engines 1-4								
	FM1	EXP(μ)	61000	EXP(μ)	210	EXP(μ)	48	.5
	FM2	EXP(μ)	82000	EXP(μ)	210	EXP(μ)	72	.5
	FM3	EXP(μ)	400	EXP(μ)	210	EXP(μ)	30	.5
Nav 1 & 2								
	FM1	Exp(μ)	3000	Exp(μ)	300	Exp(μ)	1	.9
Combat 1								
	FM1	Exp(μ)	250	Exp(μ)	300	Exp(μ)	4	.9

Table 5: Base Case Model Inputs for Case 1

1. Sensitivity to Mean Time Between Failure, Case 1

With the base-case setup, the simulation is run for ten independent three-year deployments. The output for each run is recorded, and the mean and standard error of the mean are estimated for each measure. The standard error of the mean is estimated by dividing the standard deviation of the observations by the square root of the number of observations. Table 6 is an example of the output of ten independent simulated deployments (see Appendix B).

********* Base Case for MTBF values *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	260.62	373.75	579.21	0.5892
2	292.49	351.86	585.77	0.5461
3	329.04	300.87	552.78	0.4776
4	273.25	386.53	643.69	0.5859
5	271.90	317.99	589.89	0.5391
6	279.39	399.66	575.72	0.5886
7	319.18	406.75	653.34	0.5603
8	318.27	351.59	622.01	0.5249
9	265.08	533.48	798.56	0.6681
10	247.35	374.10	636.61	0.6020
Mean	**285.66**	**379.66**	**623.76**	**0.56816**
S.E.	**8.83**	**20.13**	**22.09**	**0.01625**

Table 6: Example of simulation output.

The simulation then is re-run each time a single input is changed for the *propulsion* system. The ratio of the estimated measures and the base case is calculated for each case.

Ratio of Mean On-Station Times to Base Case Mean On-Station Time							
	Percent Change from Base MTBF						
Run #	*-20%*	*-10%*	*0%*	*5%*	*10%*	*15%*	*20%*
1	0.6407	0.7340	1	0.9904	1.0297	1.2438	1.1407
2	0.8506	0.8825	1	0.9948	1.2980	1.1120	1.2336
3	0.7946	0.9568	1	1.0013	1.1627	1.2441	1.3903
4	0.7533	0.9724	1	0.9326	1.3204	1.1181	1.2273
5	0.9971	1.0447	1	1.2640	1.3081	1.3593	1.4609
6	0.8001	0.9243	1	0.9147	0.9733	1.0360	1.1210
7	0.6617	0.7870	1	1.0668	0.8379	1.1210	1.2119
8	0.7934	0.8096	1	1.1630	1.1160	1.2167	1.1591
9	0.6254	0.7273	1	0.8304	0.9927	1.0318	1.1045
10	0.6554	0.9263	1	0.8982	1.0671	0.9730	1.1335
Mean	**0.7572**	**0.8765**	**1.0000**	**1.0056**	**1.1106**	**1.1456**	**1.2183**
S.E.	**0.0367**	**0.0340**	**0.0000**	**0.0410**	**0.0513**	**0.0376**	**0.0377**

Table 7: Example of Ratio of Mean On-Station Times

Table 7 is an example of the ratios of the mean on-station times to the base-case mean on-station time. Once the ratios are calculated for each adjusted input value of the MTBF, the values of the ratios are plotted as a function of the input. This is repeated for each measure of the model.

Figure 1 graphically illustrates the ratio of the mean on-station times to the base-case mean on-station time as a function of the percent of change in the MTBF input values for the *propulsion* system (Engines 1-4) (see Table 5). The mean on-station time has an increasing, apparently linear relation to the percent of change in the MTBF according to the model. Note that as the MTBF is increased by a given percentage, the mean on-station time is increased by nearly the same percent from the base case. Likewise, as the MTBF is decreased by a percentage, the mean on-station time is decreased by nearly the same percent from the base case over the MTBF range considered. Also shown in Figure 1 is the ratio of the mean on-station times to the base-case mean on-station time as a function of the change in MTBF of failure mode 3 (FM3) alone. This confirms that FM3 is the dominant failure mode of the ship, and adjustments in the MTBF of the other failure modes of the *propulsion* system near their base values does not have an appreciable effect on the output of the model.

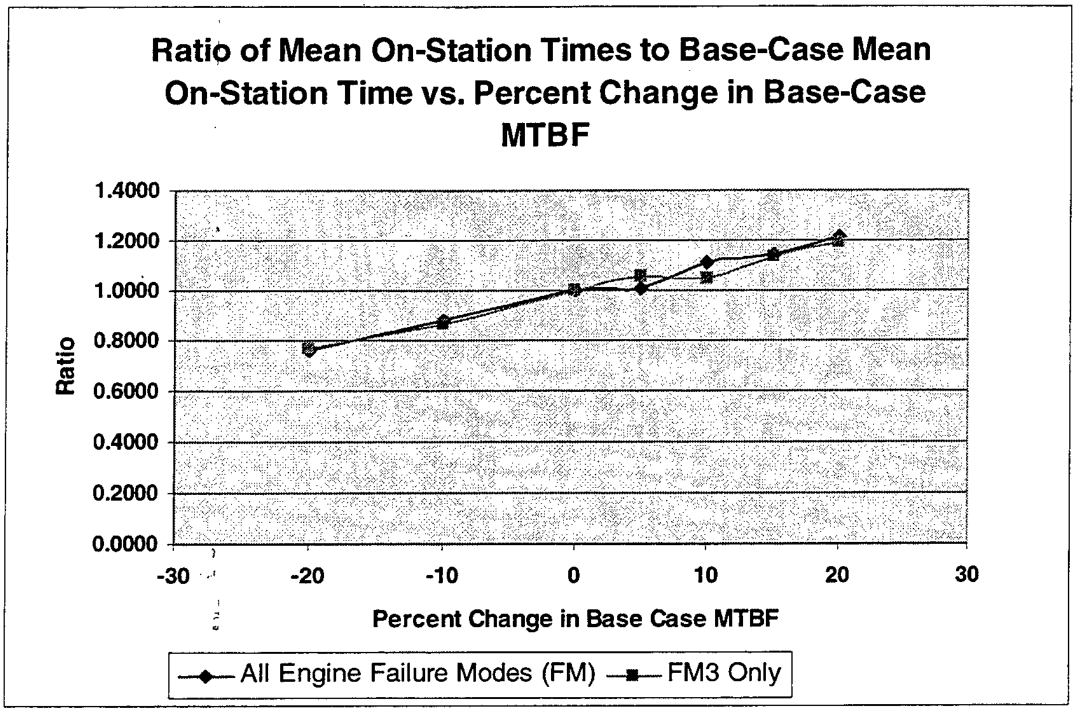

Figure 1: Case 1: Sensitivity of On-Station Time to MTBF. Base-Case Mean On-Station Time is 379.66 hours.

The measure of mean off-station time is not appreciably affected by any equal change in the MTBF's value. This is a logical conclusion since the off-station time of the ship is composed of the logistical delay, transit delay, and the repair delay, and not the time between failures. However, dramatic shifts in the relative MTBF's between the failure modes changes which failure mode's mean off-station delay will dominate.

Figure 2 graphically illustrates the ratio of the MTBBR to the base-case MTBBR as a function of the percent of change in the MTBF input values for the *propulsion* system. The MTBBR measure has an increasing linear relation to the percent of change in the MTBF according to the model. Also shown in Figure 2 is the ratio of the MTBBR to the base-case MTBBR as a function of the change in MTBF of failure mode 3 (FM3)

alone confirming that FM3 is the dominant failure mode. Figure 2 also indicates that the adjustments in MTBF of a system have more of an effect on the mean on-station time (see Figure 1) than on the MTBBR.

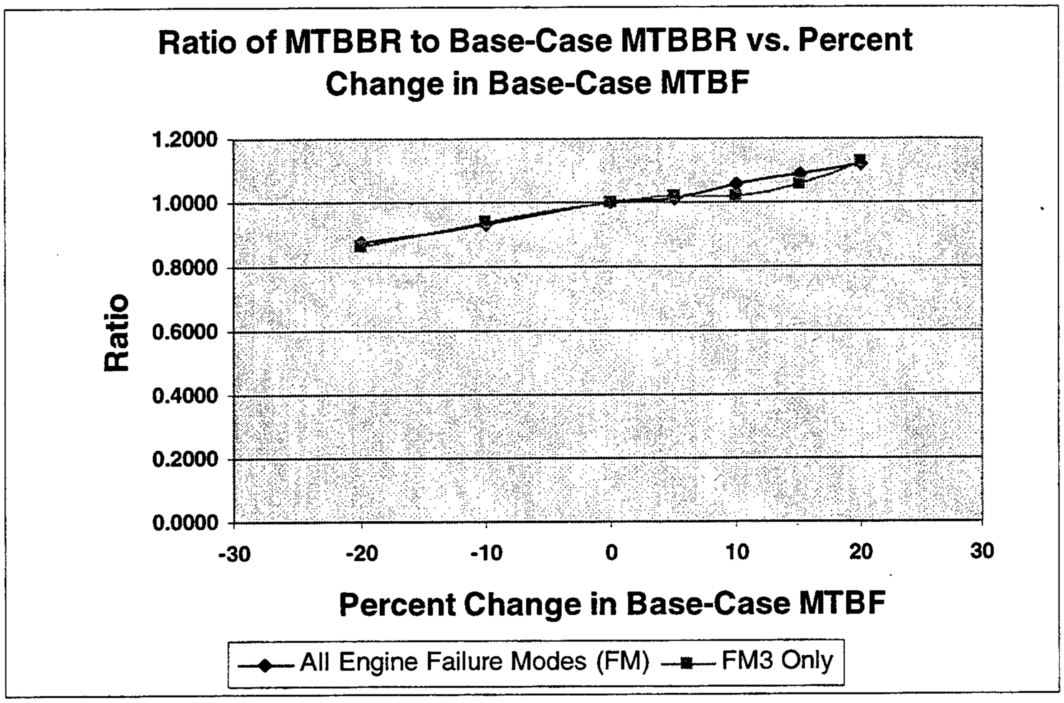

Figure 2: Case 1: Sensitivity of MTBBR to MTBF.
Base-Case MTBBR is 623.76 hours.

Figure 3 graphically illustrates the ratio of mean A_o to the base-case mean A_o as a function of the percent of change in the MTBF input values for the *propulsion* system. The mean A_o measure has an increasing linear relation to the percent of change in the MTBF similar to the relation that MTBBR and MTBF have, according to the model. As the MTBF is increased by a percentage, mean A_o increases by approximately half that percentage from the base case due to the assumed percent of *organic* repair of 50%. Likewise, as the MTBF is decreased by a percent, the mean A_o decreases by approximately half that percentage from the base case for the same reason. Figure 3 also

shows the ratio of the mean A_o to the base-case A_o as a function of the change in MTBF of FM3 alone.

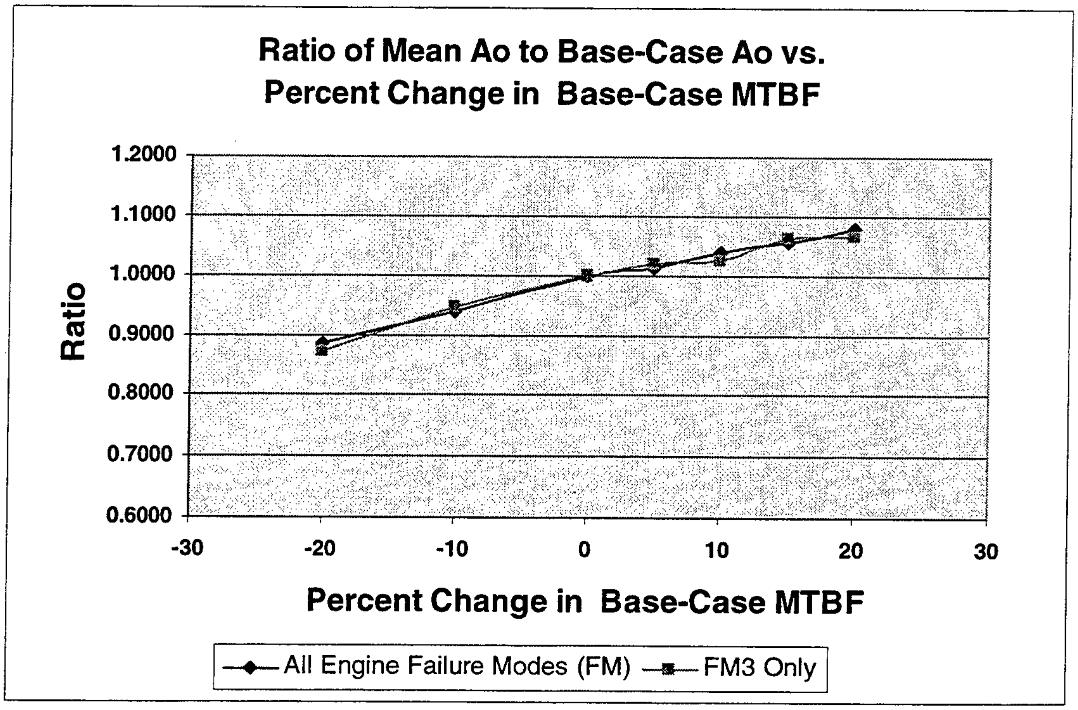

Figure 3: Case 1: Sensitivity of A_o to MTBF.
Base-Case Mean A_o is .56816.

Overall, the model is sensitive to the manipulation of the MTBF of FM3 alone. The mean times-to-failure for the other failure modes of the engines are relatively large, and achieving a ten percent increase in their respective MTBF's is not a trivial matter. A substantial increase in the mean failure time requires significant reliability engineering. However, concentrating efforts on those systems which have dominant failure modes is essential. While increasing the time between system failures would result in increases in mean on-station time, MTBBR and operational availability, it is left to further research to determine if the level of effort required to accomplish these increases is worth the rewards.

2. Sensitivity to Mean Logistics Delay Time, Case 1

Table 5 represents the base-case ship profile used to explore the sensitivity of the model to the mean logistics delay time (MLDT) inputs of the *propulsion* system. The simulation is run for ten independent deployments for each manipulation of the MLDT. In each run, the measures of effectiveness of the model are estimated. Again, the mean and standard error of the mean are calculated for each measure. The ratios of the estimated measures for each case and the base case also are calculated. Then, the ratios are plotted for each measure of the model (see Appendix B).

Figure 4 graphically illustrates the ratio of the mean off-station times to the base-case mean off-station time as a function of the percent of decrease in the MLDT input values for the *propulsion* system (see Table 5). The MLDT has a direct linear relation to the off-station time of the ship in the model. As the MLDT is decreased, the mean off-station time decreases as well. Also shown in Figure 4 is the ratio of the mean off-station times to the base-case mean off-station time as a function of changes in the MLDT of FM3 alone. Apparently the change in mean logistics delay for this one failure mode dominates the effect on off-station time of the ship.

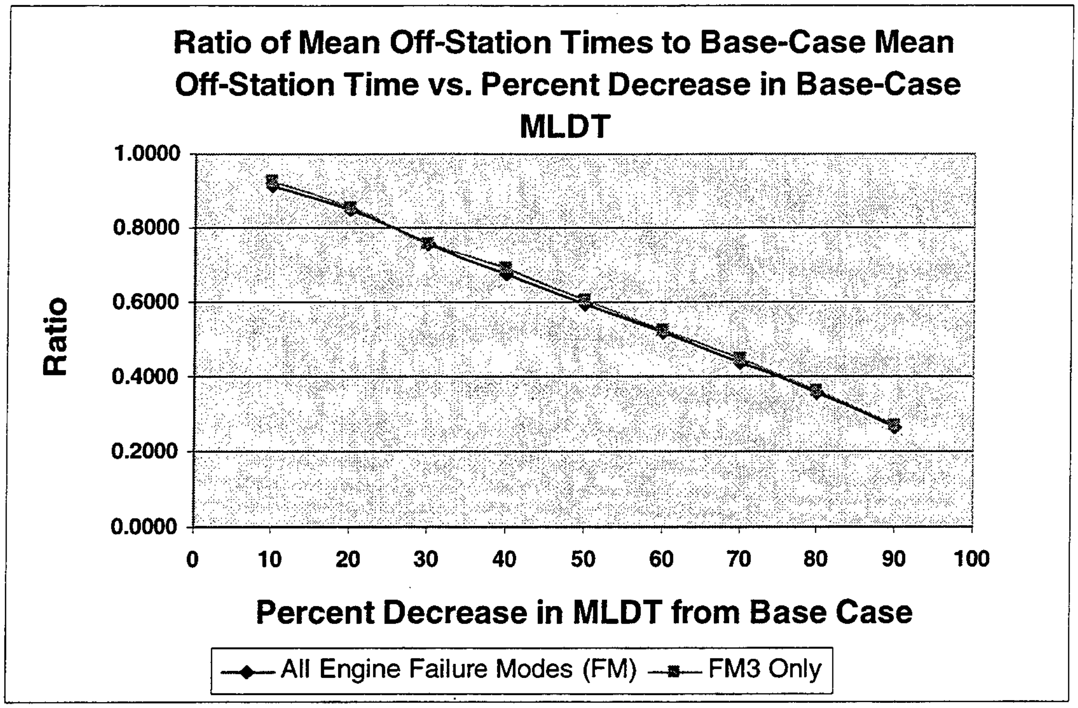

Figure 4:Case 1: Sensitivity of Off-Station Time to MLDT.
Base-Case Mean Off-Station Time is 285.66 hours.

The measure of mean on-station time is not affected by any changes in the MLDT. On-station time is dependent upon the mean time between failures.

Figure 5 graphically illustrates the ratio of the MTBBR to the base case MTBBR as a function of the percent of decrease in the MLDT of the *propulsion* system. MLDT has a direct linear relation to the MTBBR. As the MLDT input is decreased, the MTBBR decreases at a lesser rate. Figure 5 also shows the ratio as a function of changes in the MLDT of FM3 alone.

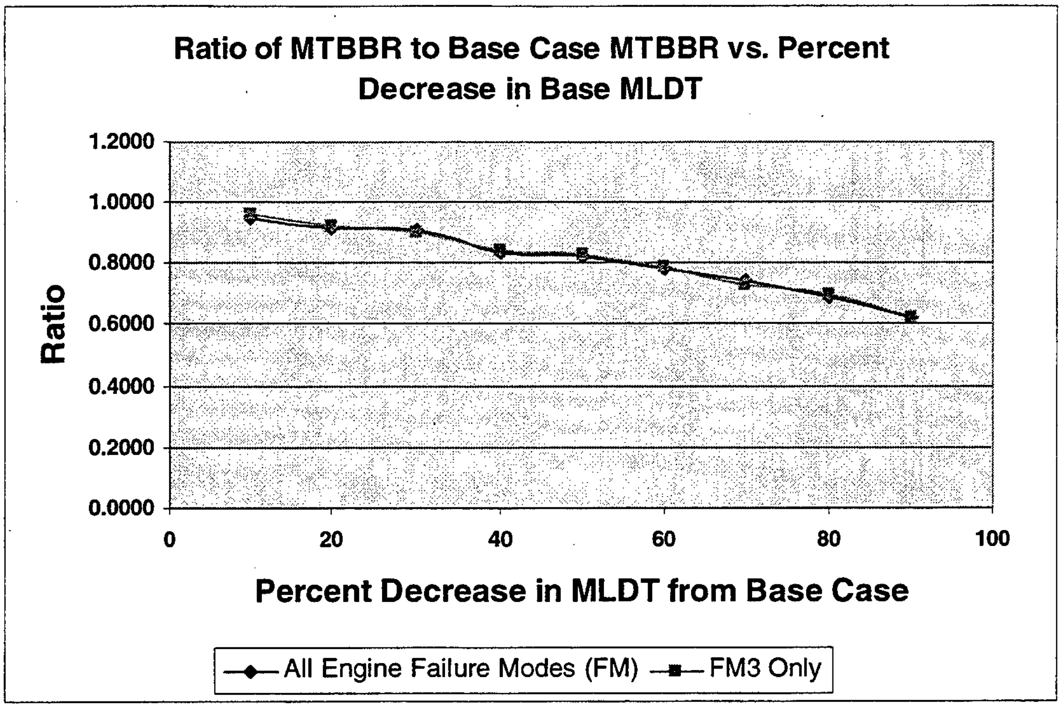

Figure 5: Case 1: Sensitivity of MTBBR to MLDT.
Base-Case MTBBR is 623.66 hours.

However, Figure 5 shows some interesting results. Decreasing the logistics delay of the model actually shrinks the mean time between base repairs. This is because the ship is experiencing more overall operating time during the three year deployment. The expected on-station time is not affected, but since the expected off-station time is decreasing, there are more *occurrences* of base repair during the entire three-year deployment. This will decrease the mean time between base repair in the model.

Figure 6 graphically illustrates the ratio of mean A_o to the base-case mean A_o as a function of the percent decrease in the MLDT input values for the *propulsion* system. Figure 6 also shows the effect on mean A_o as a function of the change in MLDT of FM3 alone. The measure of A_o has an indirect linear relation to the MLDT. As the MLDT decreases, the value of A_o increases as compared to the base case, but at a slower rate.

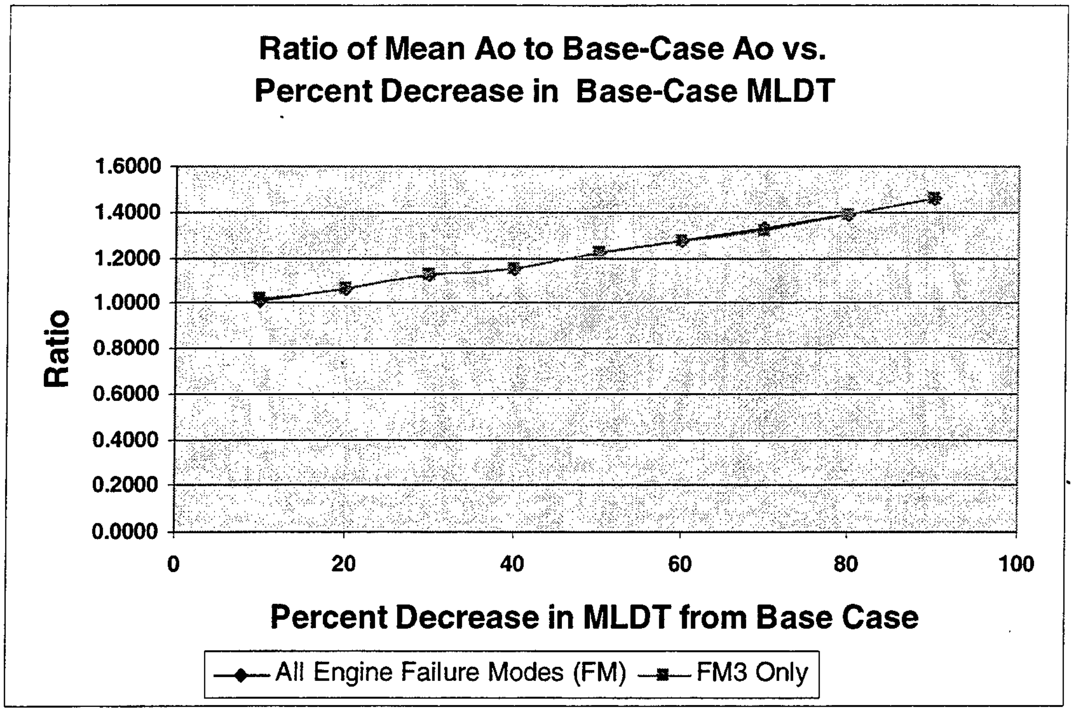

Figure 6: Case 1: Sensitivity of A_o to MLDT.
Base-Case Mean A_o is .56816.

Overall, the model is sensitive to the manipulation of the MLDT inputs. A decrease in the mean logistics delay time results in decreases that are possibly operationally significant in the mean off-station time. This indicates that improvements in historical logistical practices have an impact on the observed measures of the model. Improvements in that area would be a result of such programs as express shipments, supply visibility, and the Logistics Network (LOGNET). These improvements would be a relatively cheap way to improve the measures of the extended deployment model.

More importantly, FM3 dominates the need for logistics and changes in the logistics delay for FM3 results in changes in the measures of the model for the ship. Emphasis on logistic support must be applied to those failure modes with lesser MTBF's so that significant improvements in the measures of a system can be made. However, one

must be cautious in thinking that short logistics delays (i.e. infinite supply of spare parts) will render a system with a short time to failure (i.e. 100 hours) effective. A system with a 100 hour MTBF and a 1 hour logistics/ repair delay has an operational availability of 99%, but this is not a system for a naval ship that must be called upon to respond to any random and unpredictable crisis.

3. Sensitivity to Percent of *Organic* Repair, Case 1

Again, Table 5 represents the base-case inputs used to explore the sensitivity of the model to the percent of *organic* repair inputs for the *propulsion* system. The simulation again was run for ten independent deployments for each manipulation of the percent of *organic* repair (see Appendix B). *Organic* repair capability depends upon the degree of technical expertise, supply support, and diagnostic capability of the ship for the failures in question.

Figure 7 graphically illustrates the ratio of the mean off-station time to the base-case mean off-station time as a function of the percent of *organic* repair for the *propulsion* system. The ratio of the mean off-station time to the base-case mean off-station time as a function of changes in *organic* repair for FM3 alone is also shown in Figure 7. As the percent of *organic* repair increases, the off-station time of the ship becomes more and more dependent upon the failures of the systems on the ship with lower levels of *organic* repair. In order to possibly achieve the results shown in Figure 7, the systems onboard a ship that fail relatively frequently would need a high percent of *organic* repair.

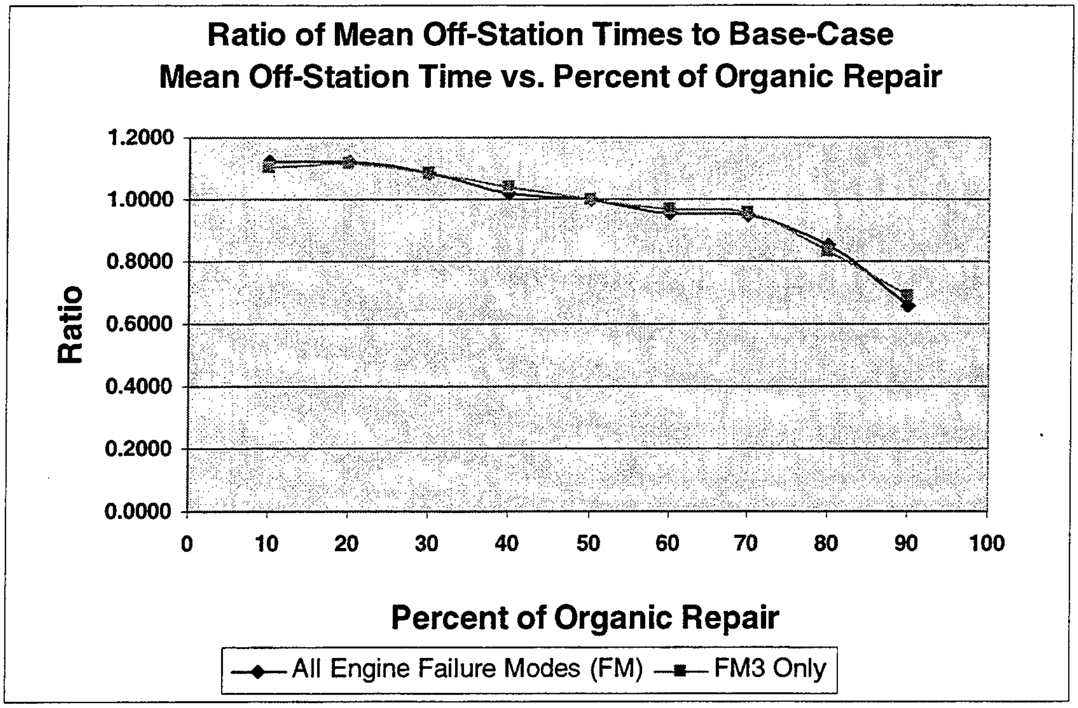

Figure 7: Case 1: Sensitivity of Mean Off-station Time to *Organic* Repair. Base-Case Mean Off-Station Time is 285.66 hours.

Figure 8 graphically illustrates the ratio of the mean on-station time to the base-case mean on-station time as a function of the percent of *organic* repair of the *propulsion* system and for FM3 alone. As the percent of *organic* repair increases, the mean on-station time of the ship increases in a non-linear fashion as shown in Figure 8.

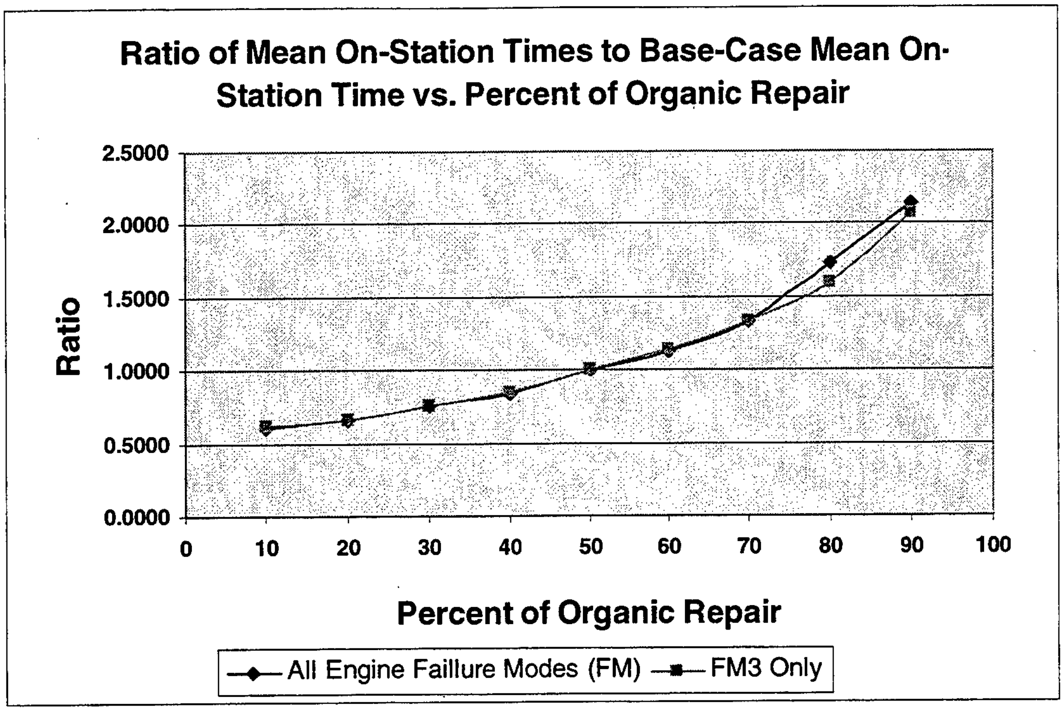

Figure 8: Case 1: Sensitivity of Mean On-station Time to Organic Repair. Base-Case Mean On-Station Time is 379.66 hours.

Figure 9 graphically illustrates the ratio of the MTBBR to the base-case MTBBR as a function of the percent of *organic* repair of the *propulsion* system and for FM3 alone. The probability of accomplishment of *organic* repair has an even greater effect on the MTBBR, as shown in Figure 9. As the percent of *organic* repair increases, the ship demands less and less base-repair support, and the MTBBR increases; from Figure 9, the effect of *organic* repair on MTBBR is distinctly non-linear.

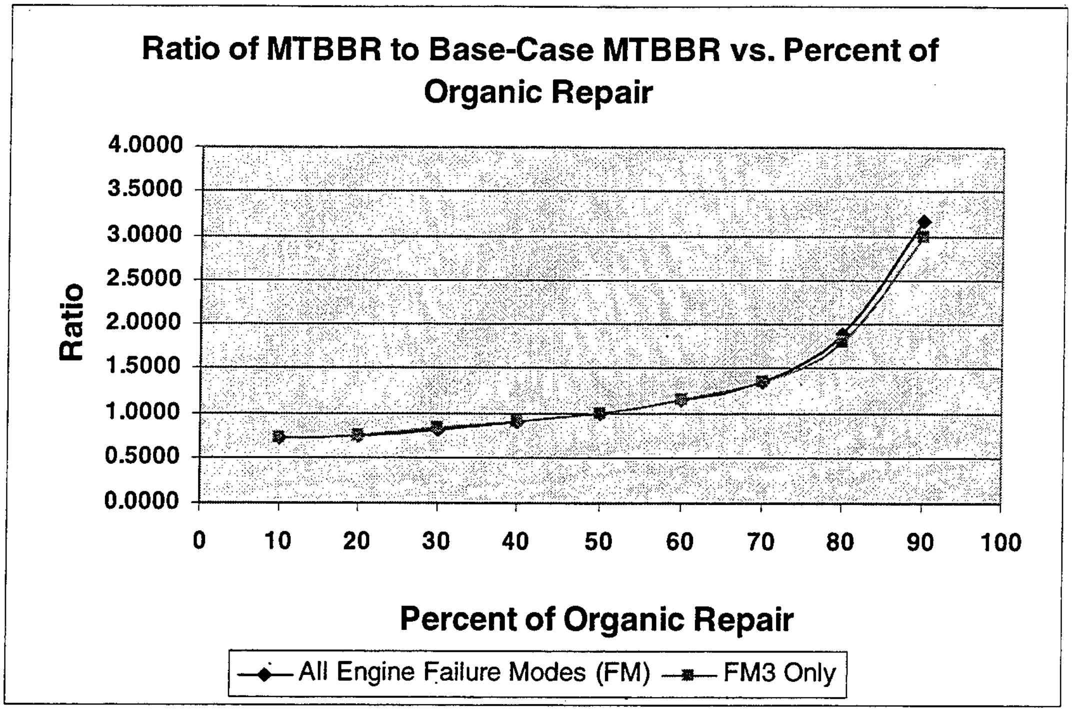

Figure 9: Case 1: Sensitivity of MTBBR to Organic Repair. Base-Case MTBBR is 623.76 hours.

Figure 10 graphically illustrates the ratio of mean A_o to the base-case A_o as a function of the percent of *organic* repair. The measure of A_o has an increasing nearly-linear relation to the percent of *organic* repair, over the range of the parameters considered.

Since there are relatively few systems represented in the model, one cannot expect to have this dramatic of an effect in reality, but it does indicate that *organic* repair is an important input into the model, particularly for those failure modes with relatively small MTBF's. However, the problem arises in achieving these levels of self-sufficiency for the ship. Capabilities such as computer diagnostics, small smart sensors, and direct links to the Original Equipment Manufacturer (OEM) or In-Service Engineering Agent (ISEA) will go a long way in increasing the ability of a ship to repair itself. But maintenance

personnel on the ship still will be required to repair the casualty. They will require the training and familiarity with the equipment in order to perform those complex maintenance actions, possibly to a higher degree than they do now. These efforts must be concentrated first on those failure modes with relatively small MTBF's, such as FM3. The value of the system simulation model is to demonstrate the value of changes to the inputs, such as increasing the probability of *organic* repair.

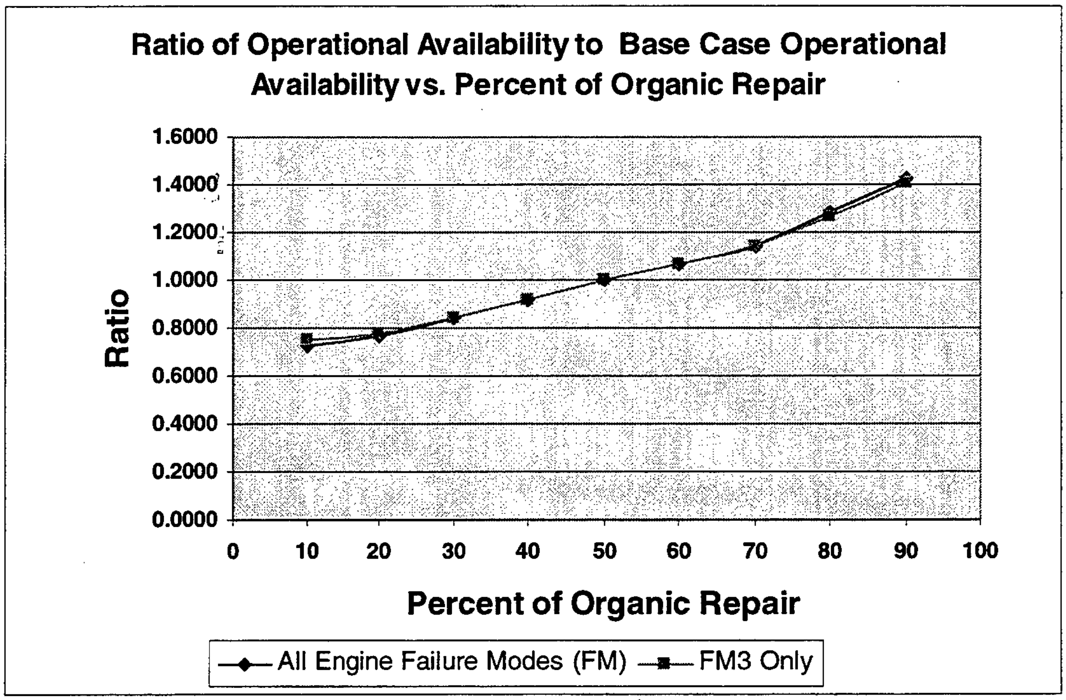

Figure 10 : Case 1: Sensitivity of A_o to Organic Repair.
Base-Case Mean A_o is .56816.

B. CASE 2: WEIBULL FAILURE DISTRIBUTIONS

In Case 1, the model was evaluated using exponential distributions to generate all times to failure. The next logical step is to model the times to failure with a "wear-out" distribution. The Weibull distribution with a shape parameter of 1.2 is used to model

"wear-out" characteristics. The Weibull distribution is a two parameter distribution: shape and scale. By logically selecting a value for the shape parameter, the scale parameter can be calculated using the estimated mean time-to-failure input data. Using this method, an assumption about the failure distribution can be made, and the data is preserved.

As in Case 1, sensitivity analysis is performed independently on three of the input parameters: MTBF, MLDT, and percent of *organic* repair. For each analysis of the these input parameters (varied individually around a single base case), ten independent simulation runs are performed, and the estimates of mean off-station time, mean on-station time, mean time between base repair (MTBBR) and operational availability (A_o) are calculated.

As in Case 1, a base-case ship profile is set up in order to generate a base-case model output for which to compare. Table 8 shows the base-case profile for Case 2.

System Name	Failure Mode	Failure Distribution	Failure Parameters	Logistics Distribution	MLDT (hrs)	Repair Distribution	MTTR (hrs)	Percent of *Organic* Repair
Engines 1-4								
	FM1	Weibull (α, β)	(1.2, 64848.37091)	EXP(μ)	210	EXP(μ)	48	.5
	FM2	Weibull (α, β)	(1.2, 87173.21991)	EXP(μ)	210	EXP(μ)	72	.5
	FM3	Weibull (α, β)	(1.2, 425.23522)	EXP(μ)	210	EXP(μ)	30	.5
Nav 1 & 2								
	FM1	Exp(μ)	3000	EXP(μ)	300	EXP(μ)	1	.9
Combat 1								
	FM1	Exp(μ)	250	EXP(μ)	300	EXP(μ)	4	.9

Table 8: Base Case Model Inputs for Case 2

The inputs for MTBF, MLDT and percent of *organic* repair then are changed independently and the measures are reevaluated. The new values for the measures of the model are compared to the values of the measures for the base case. The simulation is designed so that the only variation in the measures of the model between same-numbered runs is due to the changes in the input values. The output for Case 2 is shown in Appendix C.

1. Sensitivity to Mean Time Between Failure, Case 2

Beginning with the base case, the simulation is run for ten independent deployments. The output for each run is recorded, and the mean and standard error of the mean are calculated for each measure. The standard error is calculated by dividing the standard deviation of the observations by the square root of the number of observations (see Appendix C). Once the base-case is complete, the mean time between failure (MTBF) is manipulated and the deployments are re-run. The ratio of the estimated measures for each case and the base-case are calculated. Once the ratios are calculated for each adjusted input value of the MTBF, the values are plotted. This is repeated for each measure of the model.

Figure 11 graphically illustrates the ratio of the mean on-station times to the base-case mean on-station time as a function of the percent of change in the MTBF input values for the *propulsion* system (Engines 1-4) (see Table 8) and for FM3 alone. The mean on-station time has an increasing linear relation to the percent of change in the MTBF according to the model. Note that as the MTBF is increased from ten percent to

twenty percent, there is no real improvement.

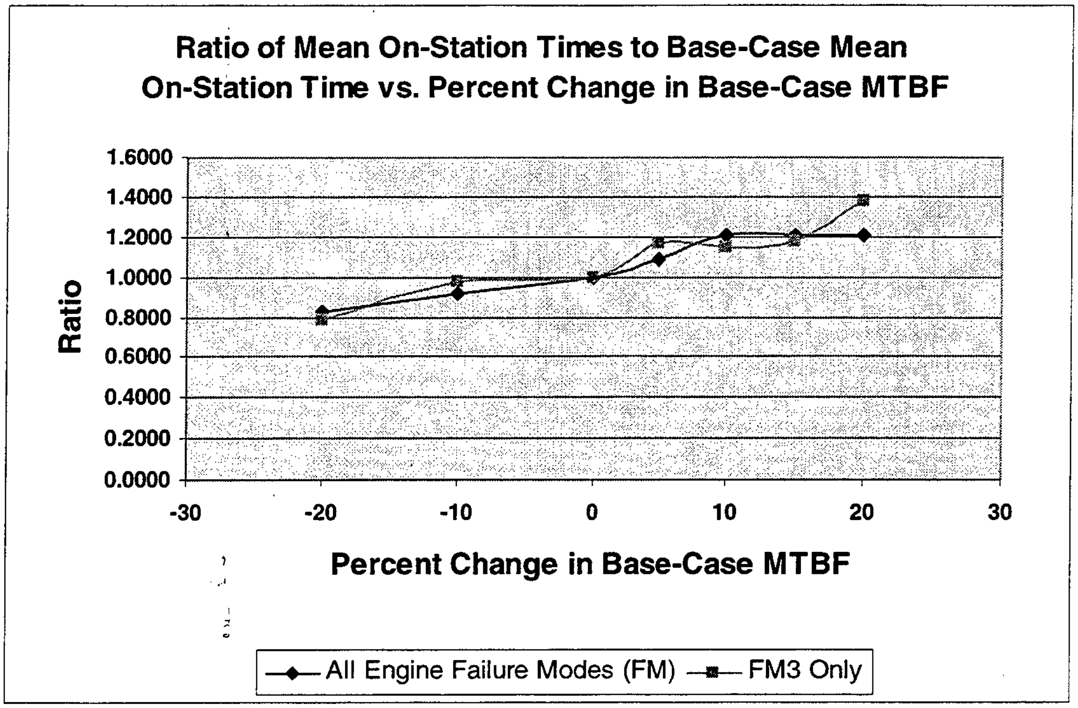

Figure 11: Case 2: Sensitivity of On-Station Time to MTBF.
Base-Case Mean On-Station Time is 602.55 hours.

As in Case 1, the measure of mean off-station time is not greatly affected by change in the MTBF of the *propulsion* system. This is a logical conclusion since the off-station time of the ship is composed of the logistical delay, transit delay, and the repair delay and not the time between failures. However, dramatic shifts in the relative MTBF's between the failure modes will change which failure mode's mean off-station delay will dominate.

Figure 12 graphically illustrates the ratio of the MTBBR to the base case MTBBR as a function of the percent of change in the MTBF input values for the *propulsion* system and for FM3 alone. The MTBBR measure again has an increasing linear relation to the percent of change in the MTBF according to the simulation. As the MTBF

increases by a percentage, MTBBR increases by a lesser percent from the base case. Likewise, as the MTBF is decreased by a percentage, the MTBBR decreases by a lesser percent from the base case. Adjustments in MTBF of a system still have more effect on the mean on-station time than corresponding changes in the MTBBR.

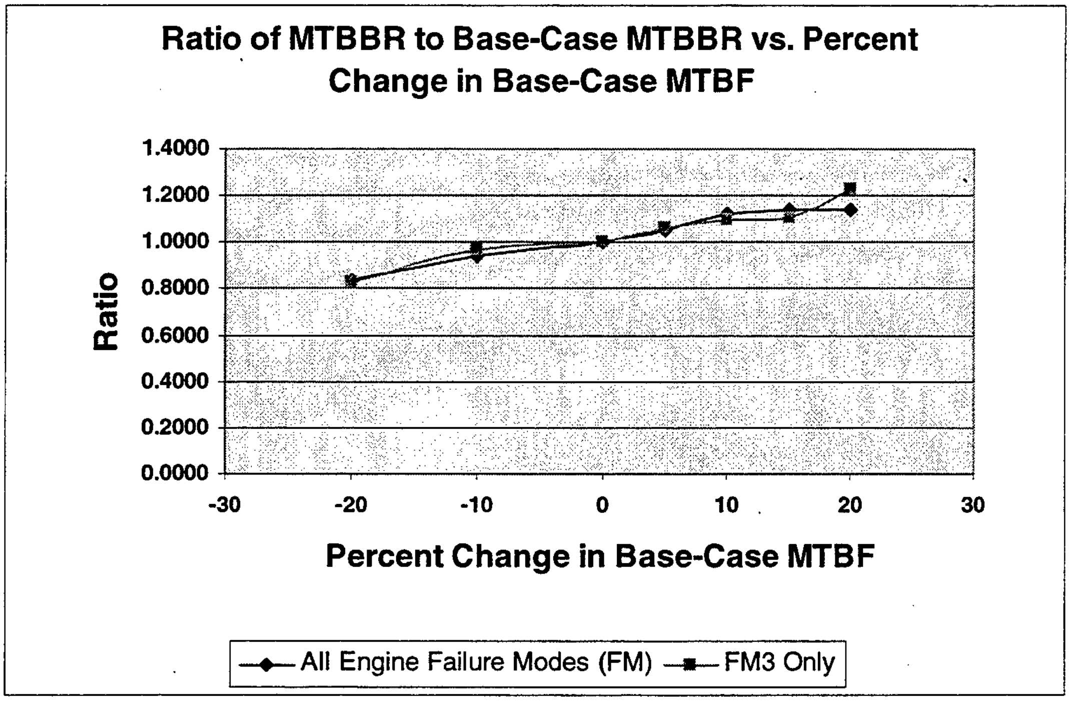

Figure 12: Case 2: Sensitivity of MTBBR to MTBF.
Base-Case MTBBR is 870.81 hours.

Figure 13 graphically illustrates the ratio of mean A_o to the base-case mean A_o as a function of the percent of change in the MTBF input values for the *propulsion* system and for FM3 alone. The measure of mean A_o has an increasing, approximately linear relation to the percent of change in the MTBF, according to the model and over the range of the parameters considered. As the MTBF is increased by a percentage, the mean A_o increases by a smaller percent from the base case. Likewise, as the MTBF is decreased

by a percentage, the mean A_o decreases by a smaller percent from the base case.

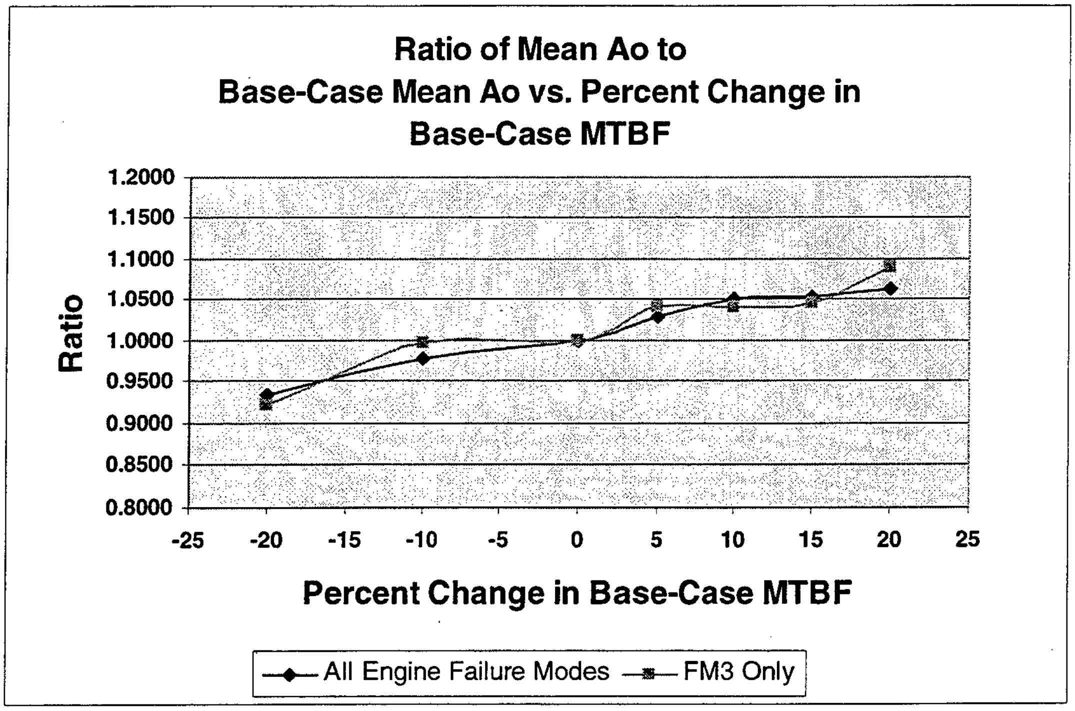

Figure 13: Case 2: Sensitivity of A_o to MTBF.
Base-Case Mean A_o is .67908.

As was true in Case 1, the model is sensitive to the manipulation of the MTBF inputs for the *propulsion* system. The model is less sensitive with times-to-failure modeled as having "wear-out" characteristics. This results from the exponential distribution's long right tail, i.e. is optimistic for times greater than the mean time-to-failure of a failure mode. However, the strong pay-off for increased performance measures is found in increasing the MTBF of FM3. While increasing the time between system failures would result in increases in mean on-station time, MTBBR and operational availability, it is left to further research to determine if the level of effort required to accomplish these increases is worth the rewards.

2. Sensitivity to Mean Logistics Delay Time, Case 2

Table 8 represents the base case used to explore the sensitivity of the model to all of the mean logistics delay time (MLDT) inputs of the *propulsion* system, and to FM3 alone. The simulation is run for ten independent three-year deployments for each manipulation of the MLDT. In each run, the measures of the model are estimated. Again, the mean and standard error are calculated for each measure (see Appendix C). The ratio of the estimated measures for each case and the base case also is calculated. Then, the ratios are plotted for each measure of the model.

Figure 14 graphically illustrates the ratio of the mean off-station time to the base-

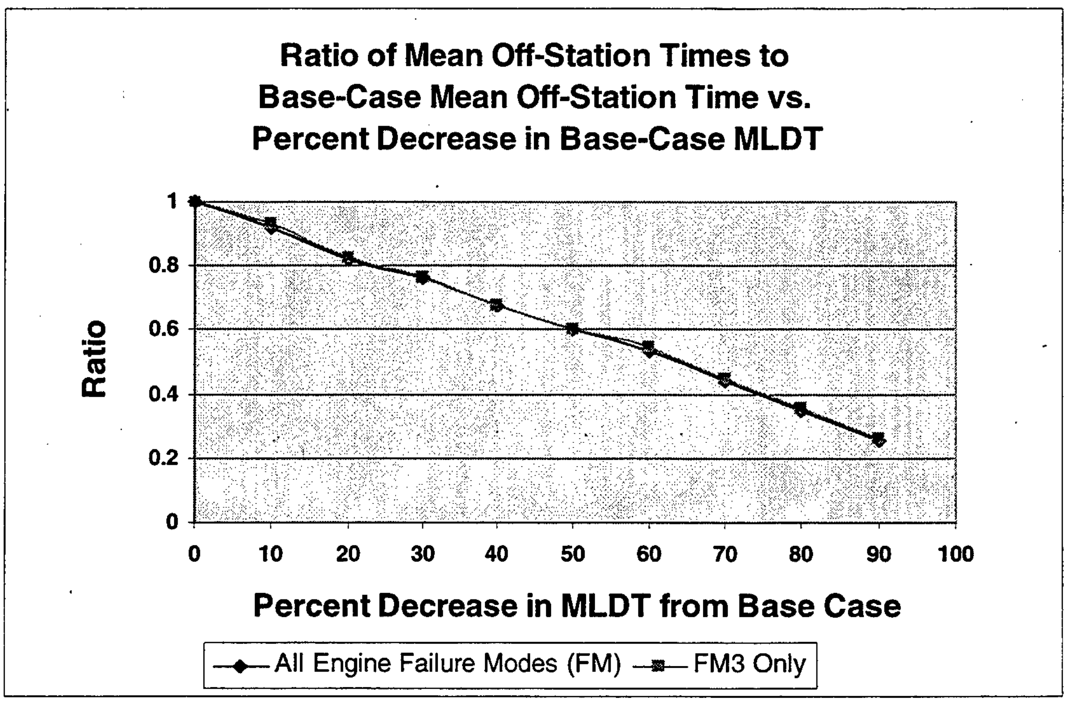

Figure 14: Case 2: Sensitivity of Off-Station Time to MLDT.
Base-Case Mean Off-Station Time is 282.46 hours.

case mean off-station time as a function of the percent of decrease in the MLDT input values for the *propulsion* system (see Table 8) and for FM3 alone. The MLDT has a

direct linear relation to the off-station time of the ship in the model. As the MLDT is decreased, the mean off-station time decreases as well.

The measure of mean on-station time is not affected by any changes in the MLDT. On-station time is dependent upon the mean time between failures as shown in the previous section.

Figure 15 graphically illustrates the ratio of the MTBBR to the base case MTBBR as a function of the percent of decrease in the MLDT of the *propulsion* system. MLDT has a nearly-linear relation to the MTBBR for the parameter range considered although not as dramatic as its affect on mean off-station time. As the MLDT input is decreased, the MTBBR decreases at a lesser rate.

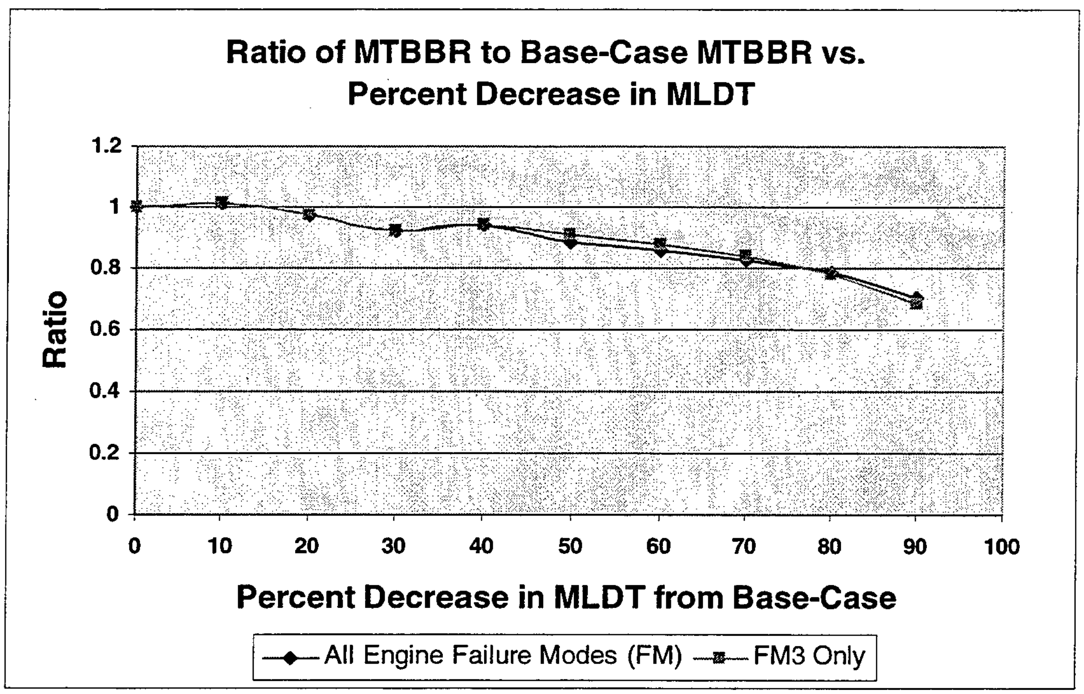

Figure 15: Case 2: Sensitivity of MTBBR to MLDT. Base-Case MTBBR is 870.81 hours.

However, Figure 15 shows some interesting results. As in Case 1, decreasing the

logistics delay of the model actually shrinks the mean time between base repairs. Again, the ship is experiencing more overall time on-station during the three year deployment, in spite of somewhat more frequent base repairs (for present assumed parameter values). The expected on-station time is not affected, but since the expected off-station time is decreasing, there are more *occurrences* of base repair during the three year deployment. This will decrease the mean time between base repair as a measure of the model.

Figure 16 graphically illustrates the ratio of the operational availability, A_o, to the base case A_o as a function of the percent decrease in the MLDT input values for the *propulsion* system. The A_o measure has an indirect linear relation to the MLDT. As the MLDT decreases, the value of A_o increases as compared to the base case.

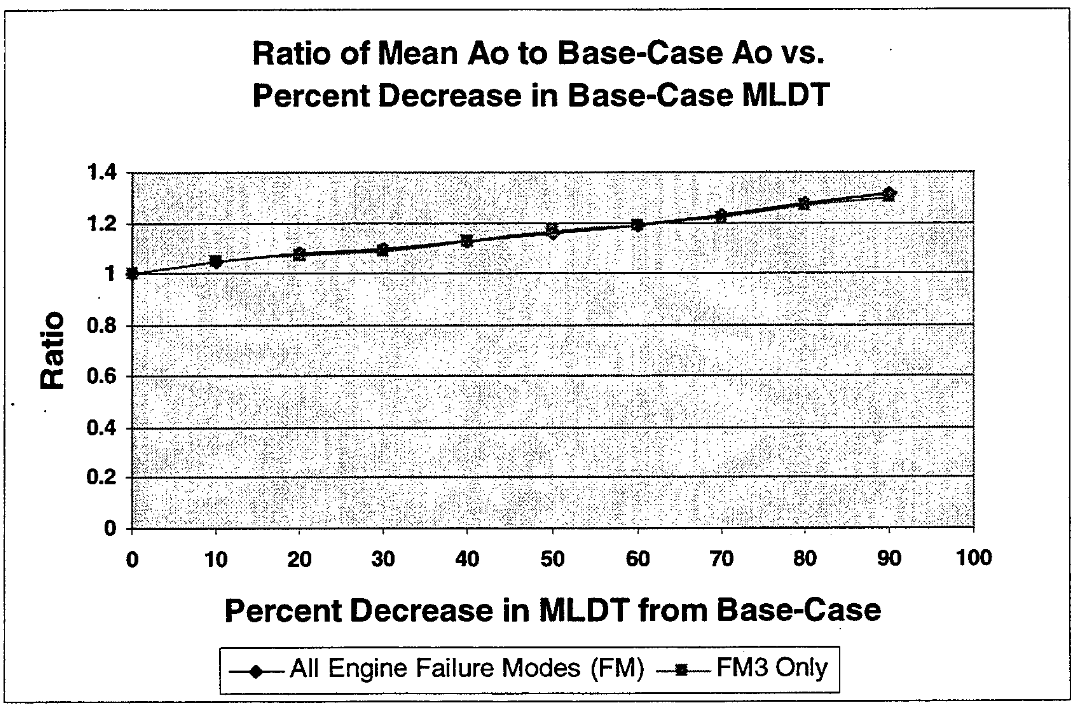

Figure 16: Case 2: Sensitivity of A_o to MLDT.
Base-Case Mean A_o is .67908.

As in Case 1, the model is significantly sensitive to the manipulation of the

MLDT inputs for the *propulsion* system. A decrease in the mean logistics delay time results in significant decreases in the mean off-station time. Improvements in that area would be a result of such programs as express shipments, supply visibility and the Logistics Network (LOGNET). These improvements could be a relatively inexpensive way to improve the measures of the extended deployment model.

3. Sensitivity to Percent of *Organic* Repair, Case 2

Again, Table 8 represents the base case inputs used to explore the sensitivity of the model to the percent of *organic* repair inputs for the *propulsion* system (Engines 1-4). The simulation again is run for ten independent deployments for each manipulation of the percent of *organic* repair (see Appendix C). *Organic* repair is a function of the amount of technical expertise, supply support, and diagnostic capability of the ship for the systems in question.

Figure 17 graphically illustrates the ratio of the mean off-station time to the base case mean off-station time as a function of the percent of *organic* repair for the *propulsion* system. As the percent of *organic* repair of the *propulsion* system increases, the off-station time of the ship becomes more and more dependent upon the failures of the systems on the ship with lower levels of *organic* repair. In order to possibly achieve the results shown in Figure 17, the majority of the systems onboard a ship would need a high percent of *organic* repair.

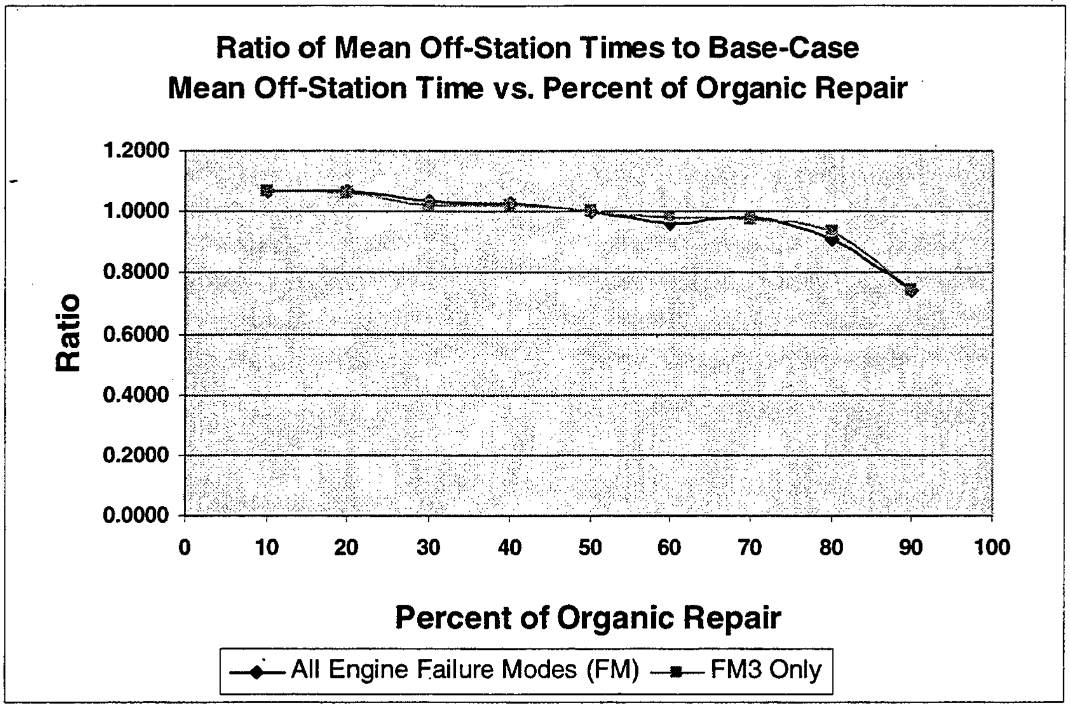

Figure 17: Case 2: Sensitivity of Mean Off-station Time to Organic Repair. Base-Case Mean Off-Station Time is 282.46 hours.

Figure 18 graphically illustrates the ratio of the mean on-station time to the base case mean on-station time as a function of the percent of *organic* repair of the *propulsion* system. As the percent of *organic* repair increases, the mean on-station time of the ship increases in a non-linear fashion as shown in Figure 18.

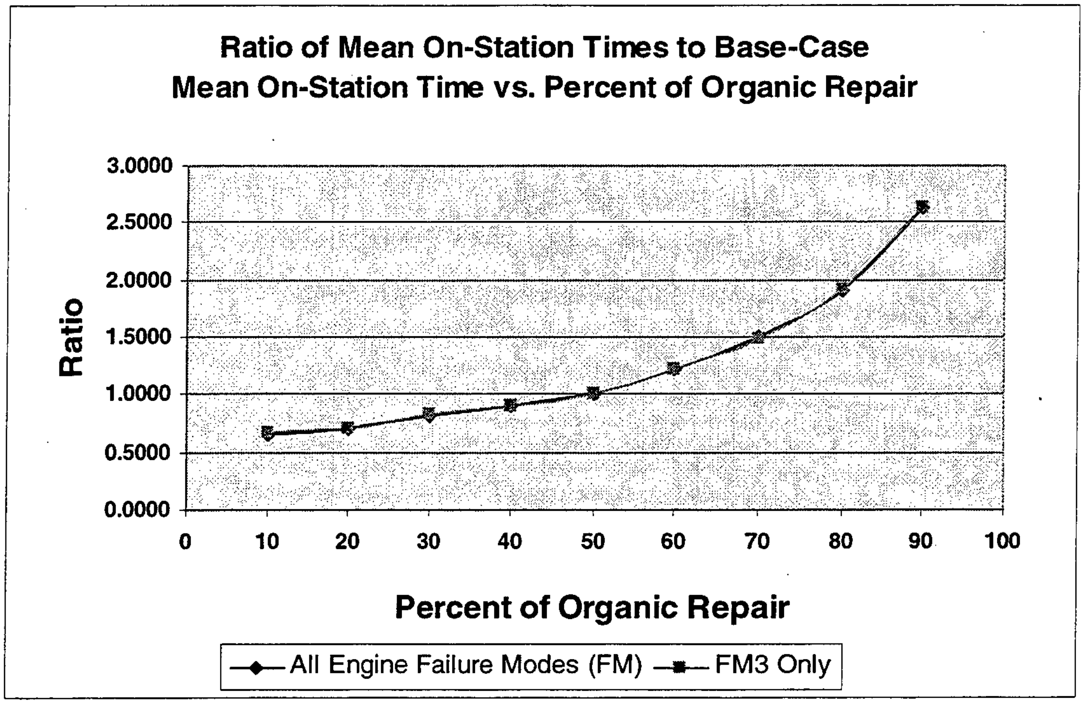

Figure 18: Case 2: Sensitivity of Mean On-station Time to Organic Repair. Base-Case Mean On-Station Time is 602.55 hours.

Figure 19 graphically illustrates the ratio of the MTBBR to the base case MTBBR as a function of the percent of *organic* repair of the *propulsion* system. *Organic* repair has an even more dramatic effect on the MTBBR. As the percent of *organic* repair increases, the ship demands less and less base repair support, and the MTBBR increases. From Figure 19, the effect of *organic* repair on MTBBR is non-linear.

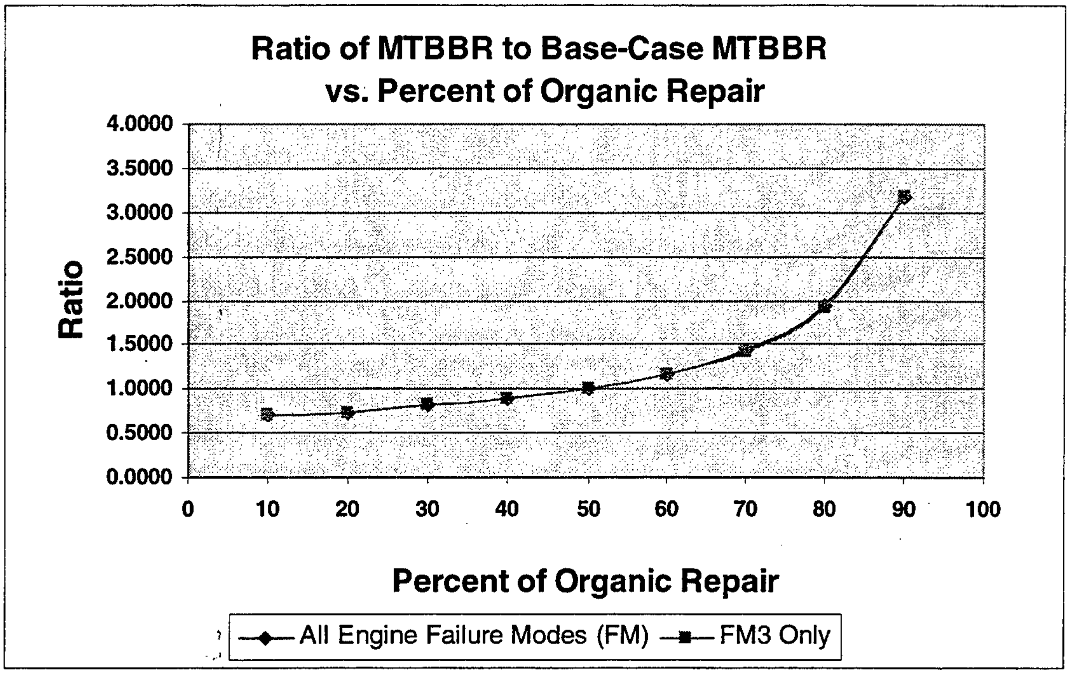

Figure 19: Case 2: Sensitivity of MTBBR to Organic Repair.
Base-Case MTBBR is 870.81 hours.

Figure 20 graphically illustrates the ratio of the operational availability, A_0, to the base case A_0 as a function of the percent of *organic* repair. The measure of A_0 has a direct relation to the percent of *organic* repair. As the percent of *organic* repair increases, the measure of A_0 increases linearly as compared to the base case.

Since there are few systems represented in the model, one cannot expect to have such a dramatic effect in reality, but the simulation does indicate that *organic* repair is an influential input of the model, even with conservative estimates of the times-to-failure. However, the problem arises in achieving these levels of self-sufficiency. Capabilities such as computer diagnostics, small smart sensors, and direct

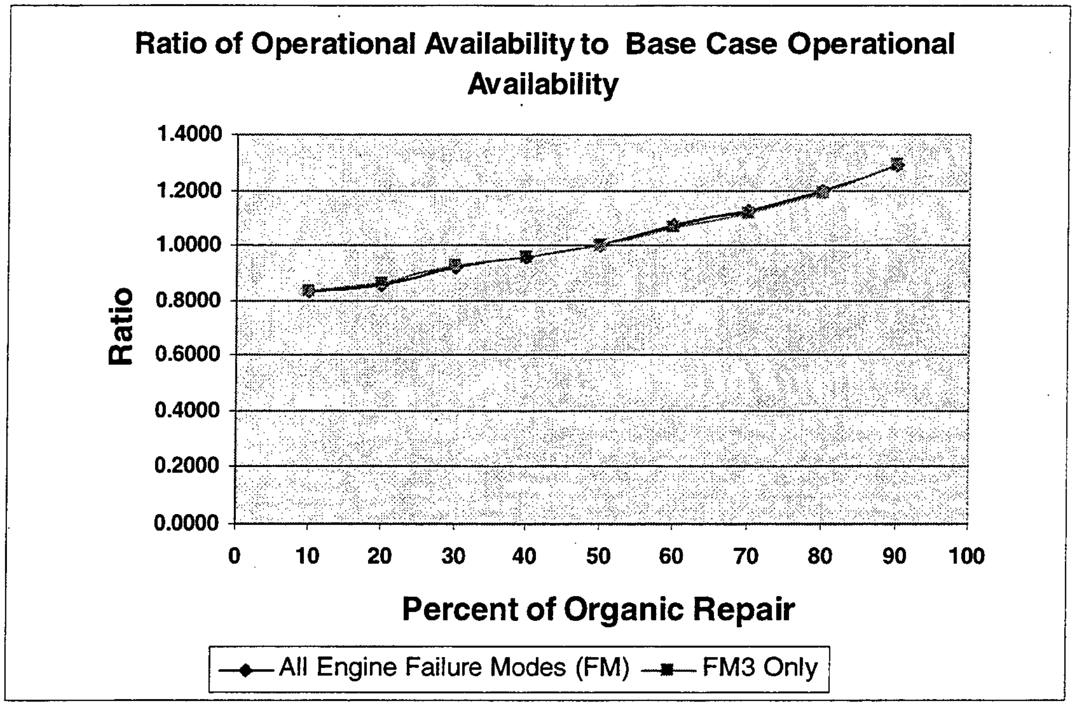

Figure 20 : Case 2: Sensitivity of A_o to *Organic* Repair.
Base-Case Mean A_o is .67908.

links to the Original Equipment Manufacturer (OEM) or In-Service Engineering Agent (ISEA) will go a long way to increasing the ability of a ship to repair itself. But maintenance personnel on the ship still *will* be required to repair the casualty. They will require training and familiarity with the equipment in order to perform those sometimes complex maintenance actions.

C. CASE 3: SENSITIVITY TO WEIBULL SHAPE PARAMETER

In Case 3, the model is evaluated using varying values of the Weibull shape parameter. As discussed earlier, the shape parameter of the Weibull distribution determines the degree of "wear-out" that a system's time-to-failure will show. With a shape parameter of one, the Weibull distribution illustrates "no-wear" failure

characteristics. With a shape parameter greater than one, the Weibull distribution illustrates "wear-out" failure characteristics. And lastly, with a shape parameter less than one the Weibull distribution illustrates "near-birth" failure characteristics.

Since the Weibull distribution is a two-parameter distribution, the second parameter, scale, is determined from the values of the shape parameter and the mean time to failure of the system. Table 9 shows the values of the scale parameter as a function of the shape parameter and the mean time to failure.

Shape parameter Value	**Mean Time to Failure (in hours)**		
	61000	**82000**	**400**
0.8	53839.21739	72374.02993	353.04405
1.0	61000.00000	82000.00000	400.00000
1.2	64848.37091	87173.21991	425.23522
1.6	68036.74983	91459.23748	446.14262
2.0	68831.12919	92527.09170	451.35167

Table 9: Scale Parameter Values as a function of MTBF and Shape Parameter

A base-case ship profile is set up in order to generate the base-case model output for which to compare. The base-case ship profile for Case 3 is shown in Table 10. After the base-case deployment is simulated, the inputs for the time-to-failure distribution parameters for the three failure modes of the *propulsion* system are changed independently. The output from these deployments is compared to the base-case deployment output (see Appendix D). The ratios of the estimated measures for each case to the base-case measures are calculated, and the values are plotted. The output for Case 3 is shown in Appendix D.

System Name	Failure Mode	Failure Distribution	Failure Parameters	Logistics Distribution	Logistics Parameter	Repair Distribution	Repair Parameter	Probability of Organic Repair
Engines 1-4								
	FM1	Weibull (α, β)	(1.0, 61000)	Exp(μ)	210	Exp(μ)	48	.5
	FM2	Weibull (α, β)	(1.0, 82000)	Exp(μ)	210	Exp(μ)	72	.5
	FM3	Weibull (α, β)	(1.0, 400)	Exp(μ)	210	Exp(μ)	30	.5
Nav 1 & 2								
	FM1	Exp(μ)	3000	Exp(μ)	300	Exp(μ)	1	.9
Combat 1								
	FM1	Exp(μ)	250	Exp(μ)	300	Exp(μ)	4	.9

Table 10: Base-Case Model Inputs for Case 3

Figure 21 graphically illustrates the ratio of the mean on-station times to the base-case mean on-station time as a function of the Weibull shape parameter input for the *propulsion* system (Engines 1-4) (see Table 10). The mean on-station time has a non-linear, *increasing* relation to the value of the Weibull shape parameter. Even with a percent of *organic* repair of 50%, the ship is able to dramatically increase its mean on-station time with equipment that must wear out to fail, specifically because short times to failures do not occur as frequently in the Weibull "wear-out" model as in the corresponding exponential model. This is a trade-off of the problem of increasing the percent of *organic* repair of the ship. However, the engineering required to cost-effectively achieve appropriate trade-offs is left for further research.

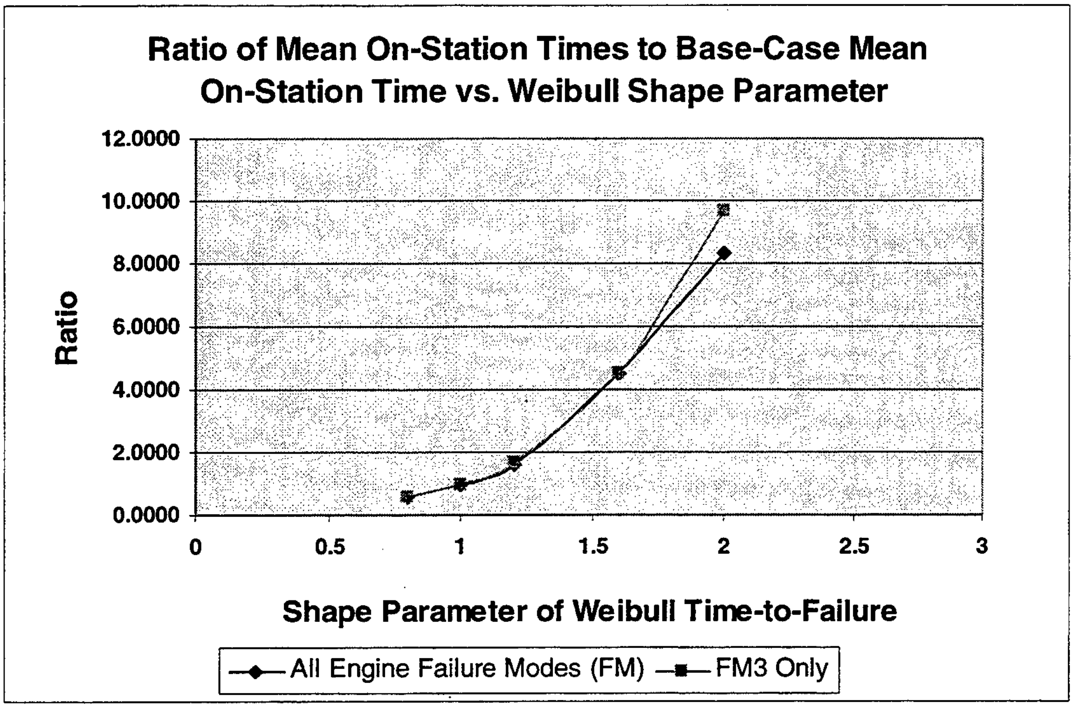

Figure 21: Case 3: Sensitivity of Mean On-Station time to Shape Parameter. Base-Case Mean On-Station Time is 379.66 hours.

Figure 22 graphically illustrates the ratio of the MTBBR to the base-case MTBBR as a function of the Weibull shape parameter input value of the *propulsion* system. The MTBBR has a non-linear, increasing relation to the value of the Weibull shape parameter. The value of the Weibull shape parameter is an indication of the frequency of base support needed on a three-year deployment.

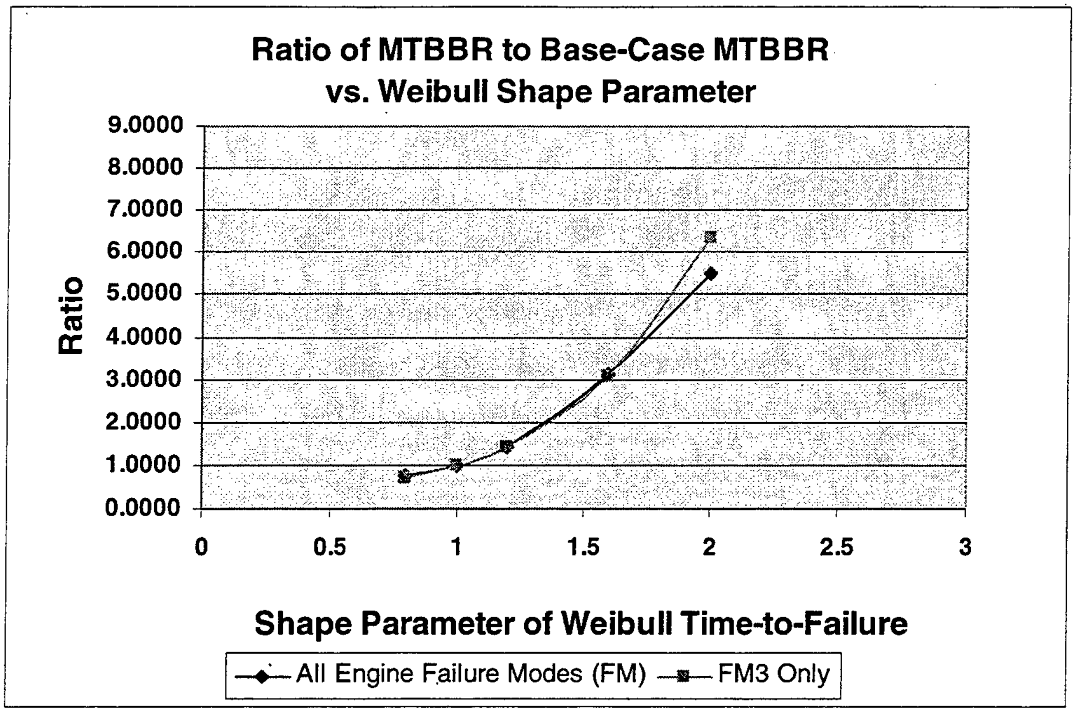

Figure 22: Case 3: Sensitivity of MTBBR to Weibull Shape Parameter. Base-Case MTBBR is 623.76 hours.

Figure 23 graphically illustrates the ratio of A_o to the base-case A_o as a function of the Weibull shape parameter value for the *propulsion* system. The measure of A_o has a non-linear, increasing relation to the Weibull shape parameter value. The value of operational availability appears to be approaching a limiting value as compared to the base case. This is a logical conclusion because the ship's mean on-station time is becoming large enough to make improvements in the ship's operational availability difficult to achieve. Also, as the mean on-station time gets larger and larger, the operational availability of the ship approaches one.

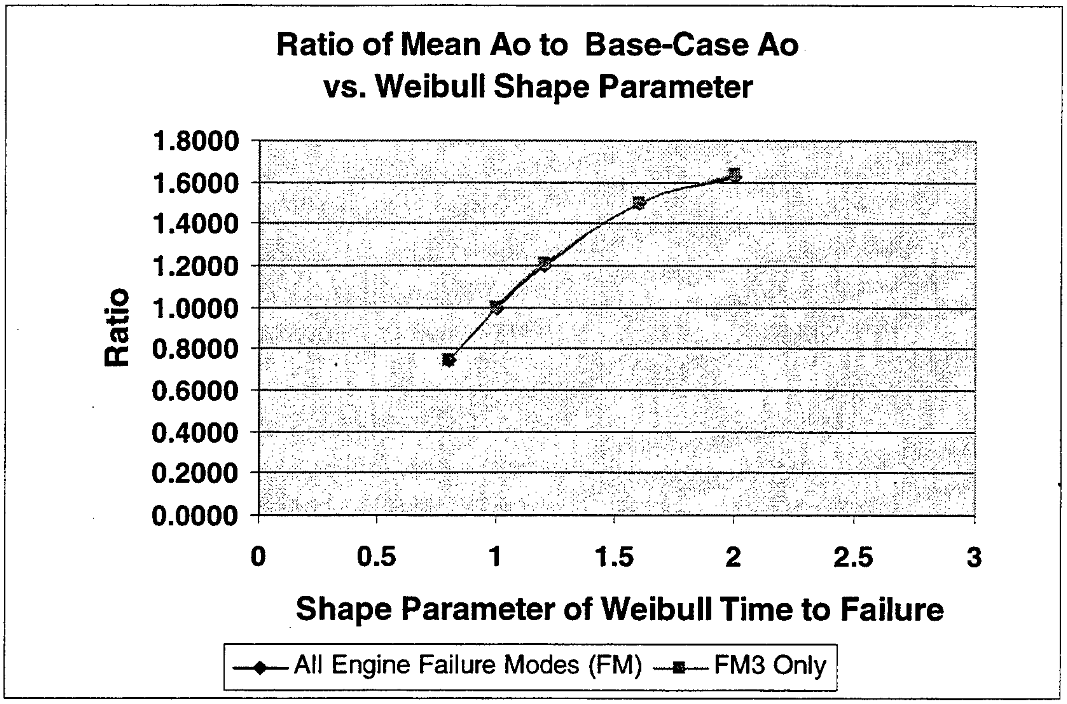

Figure 23: Case 3: Sensitivity of A_o to Weibull Shape Parameter. Base-Case Mean A_o is .56816.

The model is sensitive to changes in the shape parameter value of the Weibull time-to-failure distribution. This analysis illustrates that emphasis for engineering equipment to be used during extended deployments should be placed upon the degree of "wear-out" of that equipment. The cost effectiveness of these engineering trade-offs is left for further research.

D. CASE 4: SENSITIVITY TO TRANSIT TIME

In Case 4, the model is evaluated using increasing values of the transit delay of the ship to/from its station/base. The purpose of this analysis is to gain insight into the sensitivity of the model, based on its measures, of how far a ship's station is away from the nearest shore-based repair facility. The transit delay is run from 24 to 144 hours in 24 hour increments. The base-case model inputs are shown in Table 5 for Case 1. All

times-to-failure are distributed exponentially. After the base-case ship profile is run, the value of the transit delay is changed, and the measures of the model are re-evaluated. The ratio of the new measures and the base-case measures are calculated and plotted. The output for Case 4 is shown in Appendix E.

Figure 24 graphically illustrates the ratio of the mean off-station time to the base-case mean off-station time as a function of the transit delay of the ship. The mean off-station time has an approximately linear, increasing relation to the value of the transit delay. As the transit delay increases, the ship experiences more time off station in order to complete the repair. Also, additional failures are more likely to occur during a longer transit. In the past, deployed ships with long transit delays to the nearest shore-based repair facility could be serviced by mobile ship tenders. Since ship tenders have been removed from the inventory, long transit delay times could be overcome with an adequate repair fly-away team. This capability would originate from a shore-based repair facility servicing the area of deployment.

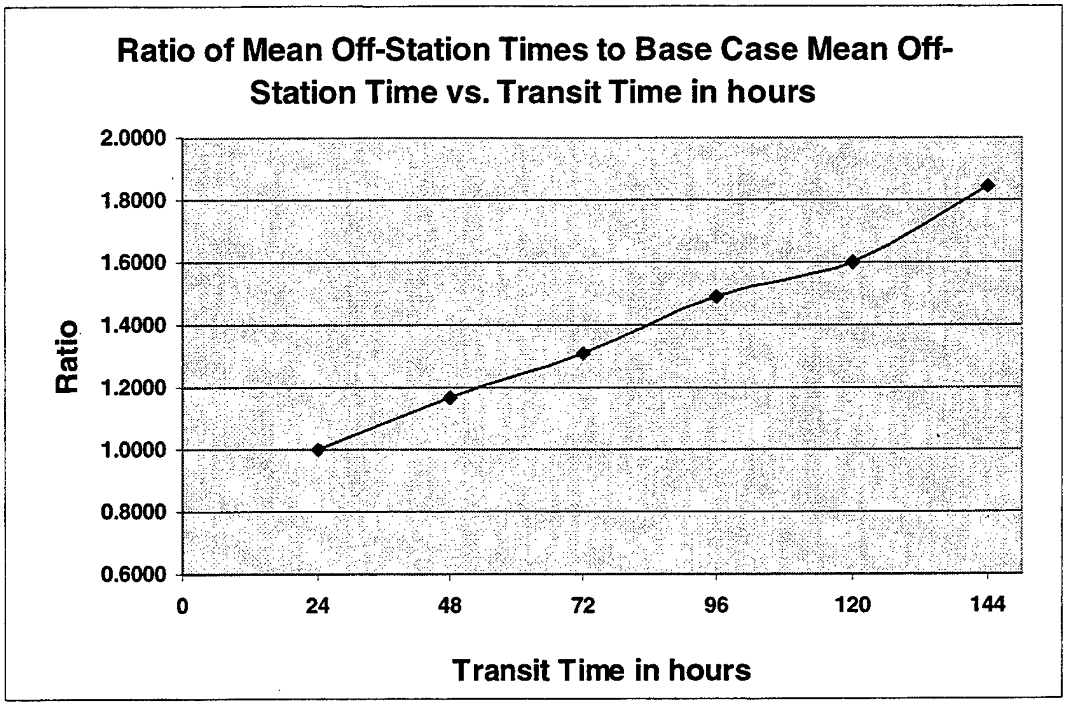

Figure 24: Case 4: Sensitivity of Mean Off-Station Time to Transit Delay. Base-Case Mean Off-Station Time is 285.66 hours.

Figure 25 graphically illustrates the ratio of the MTBBR to the base-case MTBBR as a function of the value of the transit delay of the ship. The MTBBR has a linear, decreasing relation to the value of the transit delay. This is an interesting result, but can be explained by the fact that more failures can occur during a long return transit. These failures are repaired in parallel and are viewed by the simulation as one *base repair* event.

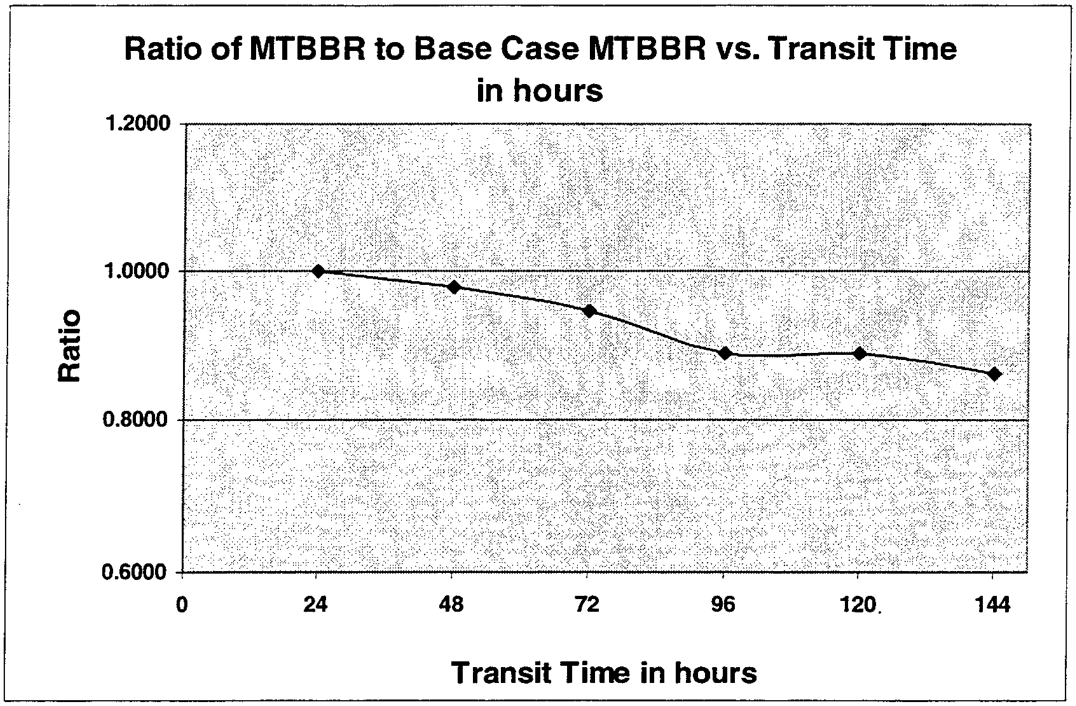

Figure 25: Case 4: Sensitivity of MTBBR to Transit Delay. Base-Case MTBBR is 623.76 hours.

Figure 26 graphically illustrates the ratio of the mean A_o to the base-case mean A_o as a function of the transit delay of the ship. The measure of A_o has an approximately linear, decreasing relation to the value of the transit delay. When a ship experiences a failure with *inorganic* repair requirements, a longer transit delay equates to a longer off-station time. The probability that a ship will be on-station when a random, unpredictable crisis occurs is smaller with a longer transit delay.

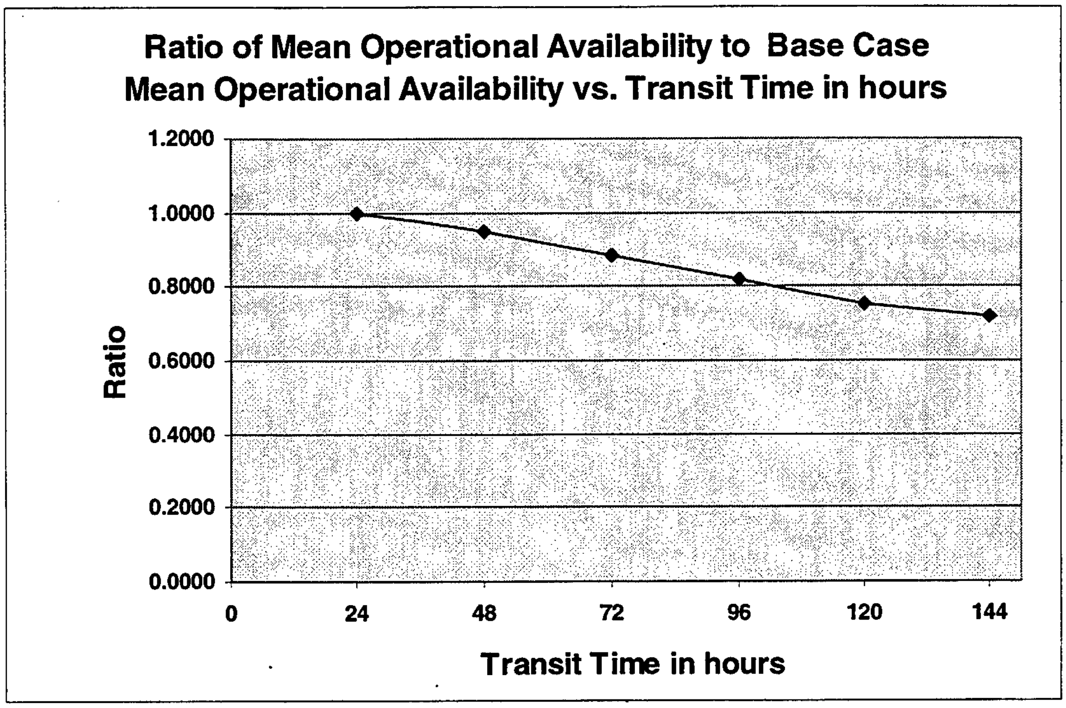

Figure 26: Case 4: Sensitivity of A_o to Transit Delay.
Base-Case Mean Ao is .56816.

The model is sensitive to the manipulation of the length of the transit delay to the nearest shore-based repair facility, but mostly in the measure of the off-station time and operational availability. This analysis illustrates the need for some mobile repair capability especially for remote areas of deployment. The cost effectiveness of such capability is left for further research.

V. CONCLUSIONS AND RECOMMENDATIONS

The model is sensitive to the value of the time between failures, but the greatest degree of benefit is from attention paid to improving those failure modes with the relatively smaller mean times to failure. However, cost should be a consideration. Once identified, these dominant failure modes are candidates for re-engineering and reliability studies. Also with increased support for these failure modes such as decreased logistics delays and increased *organic* repair support, the performance of the ship during a three-year deployment may be greatly improved. The simulation in this thesis can be used to quantify the system's operational response to such changes.

Logistics delays can be decreased using techniques such as ship-based sparing, express shipments, or shore-based inventories at overseas military repair facilities. *Organic* repair capability is improved through the use of better shipboard diagnostic equipment, or through direct links to technical experts such as the In-Service Engineering Agent or Original Equipment Manufacturer (i.e. Logistics Network). *Organic* repair capability can also be augmented by the use of Fly-Away teams from military shore-based repair facilities. The overseas maintenance capability lost by the removal of mobile ship tenders should be restored with an increase in the capability of these Fly-Away teams.

The distribution of the failure modes has an effect on the output of the simulation *only* for strong degrees of "wear-out". Weibull times-to-failure with shape parameters greater than 1.2 result in longer mean on-station times, longer MTBBR, and higher mean A_o than the exponential case. Strictly using exponential distributions underestimates the measures of effectiveness of the model. Failure modes with weak degrees of "wear-out"

(i.e. shape parameter of 1.0 to 1.2) or "near-birth" (i.e. shape parameters of 0.8 to 1.0) can be approximated closely with the exponential distribution.

This simulation assists in evaluating the trade-off benefits of increasing the logistics support, reliability, or percent of *organic* repair of a ship during a three-year deployment, but it also can be used to test policies such as when to send a ship into port for repairs to gain an increase in the mean on-station time of the ship. In the future, this simulation can assist in determining the location and capability of shore-based maintenance facilities based upon the *inorganic* repair requirements of a single-ship or multiple-ship scenarios for a three-year deployment.

Horizon is a concept which may revolutionize the way the United States Navy performs surface ship deployments. But the primary restriction of this concept is the unknown demand for *inorganic* repairs, and the possible shortfall of adequate overseas repair facilities. Regardless of the ship design, there will always be failures which cause a ship to demand some outside assistance. With such factors as age-dependent failure rates and imperfect repairs, failures will become more frequent as deployment time is increased (ship age effects are not modeled here). *Horizon* places emphasis on technology to fill the hole left behind by a smaller crew and the absence of a mobile maintenance platforms such as tenders, but the proposed technologies must be examined carefully or the readiness of the U.S. Navy could suffer.

APPENDIX A. SIMULATION INPUT FILE

#Ship name/Location
USS Myship/AOR

#Num of ship mission areas/ Ship Mission Area Names
2/AAW/MOB

#Return to port delay (in hours)
24

#Num of engine systems on ship
4

#******* ENGINE SYSTEM 1 ***********
#System Name/ System Type/ Num of Mission Areas/ Mission Area Name
GTM 1A/ENGINE/1/MOB
On Cycle/ Off Cycle/Start Survival Probability
24/24/1

#Num of Failure Modes for Engine System 1
3

#Failure Mode 1 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
TURBINE GENERATOR/EXPONENTIAL/1/61000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/48
#Organic Repair Probability
.5

#Failure Mode 2 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
POWER TURBINE/EXPONENTIAL/1/82000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/72
#Organic Repair Probability
.5

#Failure Mode 3 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
ACCESSORIES/EXPONENTIAL/1/400
#Logistics Distribution / Num of Distribution Parameters/ Parameter1

EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/30
#Organic Repair Probability
.5

#******* ENGINE SYSTEM 2 ***********
#System Name/ System Type/ Num of Mission Areas/ Mission Area Name
GTM 1B/ENGINE/1/MOB
On Cycle/ Off Cycle/Start Survival Probability
24/24/1

#Num of Failure Modes for Engine System 2
3

#Failure Mode 1 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
TURBINE GENERATOR/EXPONENTIAL/1/61000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/48
#Organic Repair Probability
.5

#Failure Mode 2 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
POWER TURBINE/EXPONENTIAL/1/82000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/72
#Organic Repair Probability
.5

#Failure Mode 3 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
ACCESSORIES/EXPONENTIAL/1/400
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/30
#Organic Repair Probability
.5

#******* ENGINE SYSTEM 3 ***********

```
#System Name/ System Type/ Num of Mission Areas/ Mission Area Name
GTM 2A/ENGINE/1/MOB
# On Cycle/ Off Cycle/Start Survival Probability
24/24/1

#Num of Failure Modes for Engine System 3
3

#Failure Mode 1 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
TURBINE GENERATOR/EXPONENTIAL/1/61000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/48
#Organic Repair Probability
.5

#Failure Mode 2 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
POWER TURBINE/EXPONENTIAL/1/82000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/72
#Organic Repair Probability
.5

#Failure Mode 3 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
ACCESSORIES/EXPONENTIAL/1/400
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/30
#Organic Repair Probability
.5


#******* ENGINE SYSTEM 4 ***********
#System Name/ System Type/ Num of Mission Areas/ Mission Area Name
GTM 2B/ENGINE/1/MOB
# On Cycle/ Off Cycle/Start Survival Probability
24/24/1

#Num of Failure Modes for Engine System 4
3
```

#Failure Mode 1 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
TURBINE GENERATOR/EXPONENTIAL/1/61000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/48
#Organic Repair Probability
.5

#Failure Mode 2 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
POWER TURBINE/EXPONENTIAL/1/82000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/72
#Organic Repair Probability
.5

#Failure Mode 3 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
ACCESSORIES/EXPONENTIAL/1/400
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/210
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/30
#Organic Repair Probability
.5

#Number of Navigation Systems
2

#************ NAVIGATION SYSTEM 1 ************
#System Name/ System Type/ Num of Mission Areas/ Mission Area Name
SPS64/NAVIGATION/1/MOB
On Cycle/ Off Cycle/Start Survival Probability
-1/-1/1

#Num of Failure Modes for Navigation System 1
1

#Failure Mode 1 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
ELECTRONIC/EXPONENTIAL/1/3000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/300
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/1

```
#Organic Repair Probability
.9

#************ NAVIGATION SYSTEM 2 ************
#System Name/ System Type/ Num of Mission Areas/ Mission Area Name
SPS10/NAVIGATION/1/MOB
# On Cycle/ Off Cycle/Start Survival Probability
-1/-1/1

#Num of Failure Modes for Navigation System 2
1

#Failure Mode 1 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
ELECTRONIC/EXPONENTIAL/1/3000
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/300
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/1
#Organic Repair Probability
.9

#Number of Combat Systems
1

#************ COMBAT SYSTEM 1 ****************
#System Name/ System Type/ Num of Mission Areas/ Mission Area Name
MK95 MOD1/COMBAT/1/AAW
# On Cycle/ Off Cycle/Start Survival Probability
10/50/1

#Num of Failure Modes for Combat System 1
1

#Failure Mode 1 Name/ Distribution/ Num of Distribution Parameters/ Parameter1
ELECTRONIC/EXPONENTIAL/1/250
#Logistics Distribution / Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/300
#Repair Distribution/ Num of Distribution Parameters/ Parameter1
EXPONENTIAL/1/4
#Organic Repair Probability
.9

#************ MISC SYSTEM *****************
# NUMBER OF MISC SYSTEMS
0
```

APPENDIX B. CASE 1 OUTPUT

The following is the simulation output for manipulations in MTBF.

	********* Base Case for MTBF values *******				********* 10% Decrease in MTBF *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	260.62	373.75	579.21	0.5892	242.62	274.33	516.94	0.5307
2	292.49	351.86	585.77	0.5461	309.94	310.52	531.82	0.5005
3	329.04	300.87	552.78	0.4776	319.26	287.87	507.78	0.4742
4	273.25	386.53	643.69	0.5859	253.76	375.86	629.62	0.5970
5	271.90	317.99	589.89	0.5391	284.40	332.21	631.29	0.5388
6	279.39	399.66	575.72	0.5886	252.80	369.39	535.08	0.5937
7	319.18	406.75	653.34	0.5603	348.67	320.11	622.12	0.4787
8	318.27	351.59	622.01	0.5249	291.98	284.66	568.38	0.4937
9	265.08	533.48	798.56	0.6681	300.80	387.99	671.13	0.5633
10	247.35	374.10	636.61	0.6020	281.09	346.54	560.87	0.5521
Mean	**285.66**	**379.66**	**623.76**	**0.56816**	**288.53**	**328.95**	**577.50**	**0.5322**
S.E.	**8.83**	**20.13**	**22.09**	**0.01625**	**10.46**	**12.78**	**17.99**	**0.01419**

	********* 20% Decrease in MTBF *******				********* 5% Increase in MTBF *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	256.06	239.48	486.52	0.4833	256.13	370.15	561.04	0.5910
2	314.34	299.30	561.42	0.4878	275.96	350.02	597.52	0.5592
3	301.84	239.07	500.09	0.4420	310.42	301.26	546.61	0.4925
4	255.29	291.17	558.08	0.5328	259.51	360.46	619.97	0.5814
5	277.53	317.07	568.17	0.5332	308.46	401.93	641.08	0.5658
6	250.53	319.75	524.66	0.5607	248.65	365.58	575.84	0.5952
7	312.70	269.13	536.90	0.4626	312.78	433.93	670.86	0.5811
8	318.63	278.96	559.45	0.4668	309.36	408.90	681.80	0.5693
9	281.35	333.64	659.99	0.5425	257.86	443.00	810.36	0.6321
10	252.27	245.17	490.10	0.4929	258.02	336.01	594.03	0.5657
Mean	**282.05**	**283.27**	**544.54**	**0.5004**	**279.72**	**377.12**	**629.91**	**0.5733**
S.E.	**8.82**	**10.99**	**16.10**	**0.01248**	**8.58**	**14.08**	**24.52**	**0.01117**

	********* 10% Increase in MTBF *******				********* 15% Increase in MTBF *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	264.49	384.85	591.62	0.5927	258.84	464.87	651.34	0.6424
2	319.43	456.72	659.73	0.5885	302.99	391.28	661.21	0.5636
3	296.07	349.83	615.15	0.5416	305.02	374.3	603.83	0.5510
4	282.19	510.38	726.52	0.6440	255.57	432.16	705.89	0.6284
5	297.58	415.97	677.88	0.5830	301.10	432.25	676.94	0.5894
6	258.08	389.00	617.66	0.6012	248.71	414.06	616.53	0.6247
7	311.91	340.80	622.35	0.5221	345.27	455.98	681.06	0.5691
8	332.27	392.36	668.88	0.5415	310.58	427.79	718.42	0.5794
9	275.55	529.60	759.73	0.6578	293.73	550.47	844.21	0.6521
10	251.47	399.19	634.79	0.6135	260.32	364.01	610.15	0.5830
Mean	**288.90**	**416.87**	**657.43**	**0.5886**	**288.21**	**430.72**	**676.96**	**0.5983**
S.E.	**8.59**	**20.01**	**16.75**	**0.01395**	**9.84**	**16.87**	**22.34**	**0.01126**

********* 20% Increase in MTBF *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	259.05	426.33	636.42	0.6220
2	319.19	434.07	703.73	0.5763
3	303.00	418.30	633.34	0.5799
4	251.38	474.40	706.29	0.6536
5	303.22	464.54	746.43	0.6051
6	244.95	448.02	628.50	0.6465
7	347.37	492.95	667.94	0.5866
8	320.76	407.53	749.10	0.5596
9	296.99	589.24	805.66	0.6649
10	254.48	424.06	678.54	0.6250
Mean	**290.04**	**457.94**	**695.60**	**0.6119**
S.E.	**11.17**	**16.90**	**18.46**	**0.01142**

The following is the simulation output for manipulations in MLDT.

********* Base Case for MLDT *******					********* 10% Decrese in MLDT *******			
Run #	AvoffTime	AvOnTime	MTBBR	Ao	AvoffTime	AvOnTime	MTBBR	Ao
1	260.62	373.75	579.21	0.5892	219.49	285.24	535.14	0.5651
2	292.49	351.86	585.77	0.5461	290.12	403.63	599.14	0.5818
3	329.04	300.87	552.78	0.4776	304.53	286.02	498.07	0.4843
4	273.25	386.53	643.69	0.5859	234.48	420.25	639.15	0.6419
5	271.90	317.99	589.89	0.5391	261.43	349.29	597.15	0.5719
6	279.39	399.66	575.72	0.5886	231.68	358.48	541.98	0.6074
7	319.18	406.75	653.34	0.5603	289.27	282.83	559.92	0.4944
8	318.27	351.59	622.01	0.5249	274.36	308.60	596.20	0.5294
9	265.08	533.48	798.56	0.6681	255.13	549.52	758.66	0.6829
10	247.35	374.10	636.61	0.6020	251.84	373.14	583.31	0.5970
Mean	**285.66**	**379.66**	**623.76**	**0.5682**	**261.23**	**361.70**	**590.87**	**0.5756**
S.E.	**8.83**	**20.13**	**22.09**	**0.01625**	**8.90**	**26.11**	**22.54**	**0.01961**

********* 20% Decrease in MLDT *******					********* 30% Decrease in MLDT *******			
Run #	AvoffTime	AvOnTime	MTBBR	Ao	AvoffTime	AvOnTime	MTBBR	Ao
1	193.40	299.96	522.96	0.6080	179.70	300.98	499.17	0.6262
2	282.17	408.31	569.79	0.5913	209.92	401.10	530.10	0.6565
3	252.44	294.17	504.57	0.5382	246.00	327.80	479.91	0.5713
4	222.11	416.95	583.57	0.6524	197.20	481.19	629.94	0.7093
5	248.24	335.18	535.79	0.5745	226.81	328.07	532.68	0.5912
6	220.40	391.79	572.27	0.6400	209.01	414.41	543.83	0.6647
7	288.15	366.29	545.47	0.5597	235.55	364.44	561.7	0.6074
8	261.09	353.46	597.51	0.5752	232.89	357.72	565.47	0.6057
9	227.40	448.53	712.47	0.6636	219.80	499.16	760.05	0.6943
10	222.03	405.03	535.28	0.6459	197.22	400.61	571.84	0.6701
Mean	**241.74**	**371.97**	**567.97**	**0.6049**	**215.41**	**387.55**	**567.47**	**0.6397**
S.E.	**9.48**	**16.21**	**18.46**	**0.01379**	**6.50**	**20.64**	**25.07**	**0.01456**

********* 40% Decrease in MLDT *******				
Run #	AvoffTime	AvOnTime	MTBBR	Ao
1	182.59	333.25	453.58	0.6460
2	198.98	382.66	546.74	0.6579
3	204.73	281.06	452.28	0.5786
4	170.82	418.71	576.72	0.7103
5	195.36	325.4	495.56	0.6249
6	187.07	410.77	519.69	0.6871
7	205.02	326.26	491.92	0.6141
8	197.09	348.64	504.54	0.6389
9	203.90	524.59	690.15	0.7201
10	172.81	346.48	499.69	0.6672
Mean	**191.84**	**369.78**	**523.09**	**0.6545**
S.E.	**4.07**	**21.67**	**22.07**	**0.01384**

********* 50% Decrease in MLDT *******			
AvoffTime	AvOnTime	MTBBR	Ao
147.20	336.86	450.67	0.6959
187.62	412.75	517.96	0.6875
176.76	318.63	445.01	0.6432
157.71	416.50	513.55	0.7254
176.83	318.34	486.16	0.6429
174.86	391.73	512.11	0.6914
179.50	334.44	504.06	0.6507
170.90	347.39	484.56	0.6703
171.66	596.84	706.19	0.7766
149.66	388.54	507.15	0.7219
169.27	**386.20**	**512.74**	**0.6906**
4.22	**26.21**	**22.97**	**0.01**

********* 60% Decrease in MLDT *******				
Run #	AvoffTime	AvOnTime	MTBBR	Ao
1	137.36	291.94	399.05	0.6800
2	164.11	432.55	499.31	0.7250
3	148.73	293.33	408.05	0.6636
4	130.95	361.57	466.13	0.7341
5	154.46	349.82	452.11	0.6937
6	146.41	417.84	521.67	0.7405
7	159.42	391.36	476.05	0.7106
8	150.89	393.08	513.75	0.7226
9	144.61	468.18	612.78	0.7640
10	140.84	445.61	540.45	0.7599
Mean	**147.78**	**384.53**	**488.94**	**0.7194**
S.E.	**3.18**	**19.12**	**20.12**	**0.01040**

********* 70% Decrease in MLDT *******			
AvoffTime	AvOnTime	MTBBR	Ao
120.07	319.85	412.42	0.7271
133.48	404.00	489.49	0.7517
130.15	319.11	401.61	0.7103
110.62	384.70	477.63	0.7767
126.96	318.40	424.80	0.7149
127.72	405.91	477.46	0.7607
134.63	346.93	407.47	0.7204
127.65	377.47	469.67	0.7473
127.72	518.89	577.82	0.8025
109.86	422.20	475.14	0.7935
124.89	**381.75**	**461.35**	**0.7505**
2.74	**19.59**	**16.78**	**0.01037**

********* 80% Decrease in MLDT *******				
Run #	AvoffTime	AvOnTime	MTBBR	Ao
1	95.76	332.55	372.2	0.7764
2	101.10	361.20	425.02	0.7813
3	111.07	337.31	383.39	0.7523
4	92.18	356.58	420.27	0.7946
5	107.26	308.32	391.14	0.7419
6	106.04	380.04	445.57	0.7819
7	108.92	352.07	417.77	0.7637
8	101.95	411.34	443.69	0.8014
9	97.76	464.21	507.93	0.8261
10	89.29	418.99	471.97	0.8243
Mean	**101.13**	**372.26**	**427.90**	**0.7844**
S.E.	**2.31**	**14.87**	**13.13**	**0.00886**

********* 90% Decrease in MLDT *******			
AvoffTime	AvOnTime	MTBBR	Ao
72.46	302.35	336.86	0.8067
84.78	366.11	375.24	0.8120
83.06	326.56	361.11	0.7972
71.41	332.18	355.20	0.8231
77.61	313.11	363.96	0.8014
81.23	343.47	376.16	0.8087
73.66	368.95	397.71	0.8336
70.37	373.37	409.07	0.8414
72.11	437.21	472.93	0.8584
68.57	420.44	447.57	0.8598
75.53	**358.38**	**389.58**	**0.8242**
1.81	**13.97**	**13.57**	**0.00728**

The following is the simulation output for manipulations in percent of *organic* repair.

***** 10% Organic Repair *******					********* 20% Organic Repair *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	347.88	179.59	403.84	0.3405	361.47	202.52	449.29	0.3591
2	360.35	266.85	516.52	0.4255	365.95	263.45	498.77	0.4186
3	326.82	245.30	461.71	0.4288	339.89	237.01	440.01	0.4108
4	286.92	231.66	449.44	0.4467	280.96	235.4	387.27	0.4559
5	318.80	212.48	392.69	0.3999	287.96	254.91	441.66	0.4696
6	246.69	206.60	398.35	0.4558	288.32	271.18	486.98	0.4847
7	334.13	213.19	406.34	0.3895	303.18	224.79	424.27	0.4258
8	378.76	220.39	516.91	0.3678	368.79	231.02	515.94	0.3852
9	322.76	306.57	516.05	0.4871	307.67	330.69	593.82	0.5180
10	267.47	164.65	356.21	0.3810	291.59	225.31	401.18	0.4359
MEAN	**319.06**	**224.73**	**441.81**	**0.4123**	**319.58**	**247.63**	**463.92**	**0.4363**
S.E.	**13.05**	**13.00**	**18.71**	**0.01411**	**11.26**	**11.23**	**19.43**	**0.01497**

********* 30% Organic Repair *******					********* 40% Organic Repair *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	338.46	223.76	433.19	0.3980	266.76	259.95	487.69	0.4935
2	334.83	291.05	525.74	0.4650	291.71	321.31	566.39	0.5241
3	339.79	212.74	441.91	0.3850	338.78	298.91	525.16	0.4687
4	234.66	341.57	541.66	0.5928	259.53	353.63	549.29	0.5767
5	305.43	304.70	524.72	0.4994	294.69	315.00	557.80	0.5167
6	263.33	301.10	494.36	0.5335	250.67	324.51	529.16	0.5642
7	289.58	250.51	481.17	0.4638	302.17	318.53	554.67	0.5132
8	362.75	272.27	544.30	0.4288	316.19	282.42	598.61	0.4718
9	320.34	419.63	649.73	0.5671	298.52	390.64	707.79	0.5668
10	287.18	240.49	454.89	0.4558	283.93	283.54	511.83	0.4997
MEAN	**307.64**	**285.78**	**509.17**	**0.4789**	**290.30**	**314.84**	**558.84**	**0.5195**
S.E.	**12.454**	**19.524**	**20.224**	**0.02185**	**8.41**	**11.88**	**19.21**	**0.01225**

********* 50% Organic Repair *******					********* 60% Organic Repair *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	260.62	373.75	579.21	0.5892	251.44	338.55	603.39	0.5738
2	292.49	351.86	585.77	0.5461	273.18	434.88	672.66	0.6142
3	329.04	300.87	552.78	0.4776	304.02	424.63	690.31	0.5828
4	273.25	386.53	643.69	0.5859	275.15	601.80	876.95	0.6862
5	271.90	317.99	589.89	0.5391	282.40	349.89	663.14	0.5534
6	279.39	399.66	575.72	0.5886	242.47	396.09	623.71	0.6203
7	319.18	406.75	653.34	0.5603	285.65	350.01	684.56	0.5506
8	318.27	351.59	622.01	0.5249	280.01	349.31	677.73	0.5551
9	265.08	533.48	798.56	0.6681	271.22	529.58	880.89	0.6613
10	247.35	374.10	636.61	0.6020	245.76	465.17	773.66	0.6543
MEAN	**285.66**	**379.66**	**623.76**	**0.5682**	**271.13**	**423.99**	**714.70**	**0.6052**
S.E.	**8.83**	**20.13**	**22.09**	**0.01625**	**6.12**	**27.73**	**30.80**	**0.01567**

********* 70% Organic Repair *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	229.04	447.85	721.39	0.6616
2	271.05	493.10	813.14	0.6453
3	277.21	452.05	846.88	0.6199
4	308.99	680.02	954.91	0.6876
5	257.89	380.71	770.07	0.5962
6	235.18	429.77	806.00	0.6463
7	272.39	419.57	749.63	0.6064
8	339.87	521.76	834.70	0.6056
9	278.54	633.82	1018.54	0.6947
10	231.94	539.56	849.86	0.6994
MEAN	**270.21**	**499.82**	**836.51**	**0.6463**
S.E.	**11.06**	**30.38**	**28.70**	**0.01228**

********* 80% Organic Repair *******			
AvOffTime	AvOnTime	MTBBR	Ao
192.92	478.54	895.28	0.7127
195.16	561.48	996.58	0.7421
215.79	543.62	1099.15	0.7158
342.42	902.39	1244.81	0.7249
268.22	512.38	983.60	0.6564
273.90	922.56	1316.11	0.7711
236.02	578.50	1221.79	0.7102
290.11	584.29	1115.61	0.6682
254.53	808.47	1284.97	0.7606
155.50	649.16	1519.91	0.8068
242.46	**654.14**	**1167.78**	**0.7269**
17.34	**51.62**	**59.02**	**0.01442**

********* 90% Organic Repair *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	166.14	554.75	1441.78	0.7695
2	182.46	765.85	2257.87	0.8076
3	172.34	1135.45	2496.69	0.8682
4	180.87	811.37	1984.47	0.8177
5	196.41	626.13	1512.81	0.7612
6	238.52	864.26	1654.16	0.7837
7	206.04	658.22	1852.00	0.7616
8	224.13	903.44	1804.10	0.8012
9	188.47	966.49	2043.40	0.8368
10	121.93	671.17	2617.23	0.8463
MEAN	**187.73**	**795.71**	**1966.45**	**0.8054**
S.E.	**5.69**	**13.32**	**19.91**	**0.19268**

APPENDIX C. CASE 2 OUTPUT

The following is the simulation output for manipulations in MTBF.

********* Base Case for MTBF values *******					********* 10% Decrease in MTBF *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	255.48	541.35	796.83	0.6794	245.2	415.94	695.93	0.6291
2	360.03	722.99	962.69	0.6676	318.89	529.73	822.09	0.6242
3	284.9	648.06	845.5	0.6946	286.55	562.39	774.03	0.6625
4	254.96	645.42	900.38	0.7168	253.91	611.35	894.1	0.7066
5	273.69	591.47	865.16	0.6837	281.61	552.46	834.07	0.6624
6	257.77	474.86	712.83	0.6482	257.43	578.96	786.19	0.6922
7	310.86	497.33	784.42	0.6154	293.05	445.65	759.8	0.6033
8	318.33	540.37	858.71	0.6293	304.59	547.33	825.3	0.6425
9	260.1	725.02	1063.94	0.7360	267.54	669.37	936.91	0.7145
10	248.47	638.61	917.67	0.7199	237.61	532.87	793.83	0.6916
Mean	**282.46**	**602.55**	**870.81**	**0.67908**	**274.64**	**544.61**	**812.23**	**0.6629**
S.E.	**11.52**	**27.85**	**31.18**	**0.01257**	**8.43**	**23.16**	**21.54**	**0.01195**

********* 20% Decrease in MTBF *******					********* 5% Increase in MTBF *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	259.27	508.94	687.35	0.6625	262.02	614.7	876.72	0.7011
2	330.8	521.62	777.21	0.6119	320.23	678.28	961.53	0.6793
3	299.89	459.94	664.85	0.6053	291.39	623.82	829.4	0.6816
4	243.46	554.27	797.73	0.6948	247.2	576.65	850.42	0.6999
5	286.92	426.04	712.96	0.5976	290.46	686.03	976.49	0.7026
6	259.8	457.8	645.84	0.6380	216.85	565.51	759.36	0.7228
7	309.18	491.07	713.74	0.6137	303.08	534.86	812.54	0.6383
8	308.25	386.91	676.24	0.5566	315.27	534.37	823.09	0.6289
9	261.22	639.04	900.26	0.7098	230.64	1195.43	1505.29	0.8383
10	250.32	458.08	728.07	0.6466	239.28	536.51	824.27	0.6916
Mean	**280.91**	**490.37**	**730.43**	**0.6337**	**271.64**	**654.62**	**921.91**	**0.6984**
S.E.	**9.47**	**22.45**	**24.13**	**0.01471**	**11.75**	**62.66**	**68.17**	**0.01805**

********* 10% Increase in MTBF *******					********* 15% Increase in MTBF *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	279.67	624.73	846.05	0.6908	262.18	632.56	840.51	0.7070
2	357.26	782.27	1095.7	0.6865	335.24	826.44	1072.32	0.7114
3	280.52	783.87	1005.75	0.7365	295.52	654.75	918.59	0.6890
4	251.44	675.23	959.76	0.7287	274.44	795.7	1030.51	0.7436
5	265.07	738.6	1043.82	0.7359	306.65	735.31	1003.37	0.7057
6	231.32	715.20	913.88	0.7556	240.39	695.51	935.9	0.7431
7	324.25	565.82	782.18	0.6357	307.17	548.98	856.15	0.6412
8	345.96	599.27	912.64	0.6340	314.78	658.96	973.73	0.6767
9	249.6	863.02	1112.62	0.7757	227.13	930.2	1273.06	0.8038
10	269.4	877.29	1100.82	0.7651	283.05	747.93	992.8	0.7255
Mean	**285.45**	**722.53**	**977.32**	**0.7144**	**284.66**	**722.63**	**989.69**	**0.7147**
S.E.	**13.51**	**33.81**	**36.00**	**0.01604**	**10.78**	**34.59**	**39.06**	**0.01388**

********* 20% Increase in MTBF *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	242.42	647.17	889.59	0.7275
2	358.06	785.65	1011.74	0.6869
3	287.25	748.35	997.25	0.7226
4	264.94	723.49	988.42	0.7320
5	286.05	812.66	1098.71	0.7397
6	238.15	737.29	939.32	0.7559
7	302.44	584.59	887.04	0.6590
8	321.46	558.28	851.36	0.6346
9	210.81	971.01	1238.1	0.8216
10	232	690.76	1029.23	0.7486
Mean	**274.36**	**725.93**	**993.08**	**0.7228**
S.E.	**14.36**	**37.61**	**36.18**	**0.01668**

The following is the simulation output for manipulations in MLDT.

********* Base Case for MLDT *******					********* 10% Decrese in MLDT *******			
Run #	AvoffTime	AvOnTime	MTBBR	Ao	AvoffTime	AvOnTime	MTBBR	Ao
1	255.48	541.35	796.83	0.6794	229.42	532.65	833.51	0.6990
2	360.03	722.99	962.69	0.6676	319.36	855.81	1001.08	0.7282
3	284.9	648.06	845.5	0.6946	258.55	556.76	792.02	0.6829
4	254.96	645.42	900.38	0.7168	235.71	580.21	791.19	0.7111
5	273.69	591.47	865.16	0.6837	273.31	826.89	1057.89	0.7516
6	257.77	474.86	712.83	0.6482	214.9	549.08	763.97	0.7187
7	310.86	497.33	784.42	0.6154	283.9	609.73	817.03	0.6823
8	318.33	540.37	858.71	0.6293	289.84	555.08	793.71	0.6570
9	260.1	725.02	1063.94	0.7360	262.23	799.54	1154.1	0.7530
10	248.47	638.61	917.67	0.7199	227.51	608.17	835.69	0.7278
Mean	**282.46**	**602.55**	**870.81**	**0.6791**	**259.47**	**647.39**	**884.02**	**0.7112**
S.E.	**11.52**	**27.85**	**31.18**	**0.01257**	**10.43**	**40.26**	**42.93**	**0.00985**

********* 20% Decrease in MLDT *******					********* 30% Decrease in MLDT *******			
Run #	AvoffTime	AvOnTime	MTBBR	Ao	AvoffTime	AvOnTime	MTBBR	Ao
1	223.01	577.99	777.45	0.7216	201.42	624.75	826.17	0.7562
2	283.97	691.47	823.03	0.7089	238.94	616.57	828.78	0.7207
3	224.46	543.47	746.6	0.7077	223.56	671.40	767.11	0.7502
4	215.09	706.03	890.42	0.7665	182.72	640.33	798.1	0.7780
5	236.85	655.31	922.92	0.7345	215.01	601.85	851.58	0.7368
6	212.00	562.28	731.26	0.7262	195.8	597.7	727.37	0.7532
7	245.89	518.71	743.36	0.6784	245.92	557.49	736.45	0.6939
8	258.31	598.45	830.57	0.6985	226.6	484.43	675.47	0.6813
9	206.24	887.24	1141.02	0.8114	232.15	823.53	977.48	0.7801
10	207.34	694.2	901.54	0.7700	189.94	598.03	787.97	0.7590
Mean	**231.32**	**643.52**	**850.82**	**0.7324**	**215.21**	**621.61**	**797.65**	**0.7409**
S.E.	**7.96**	**34.45**	**38.99**	**0.01256**	**6.87**	**27.50**	**26.18**	**0.01049**

********* 40% Decrease in MLDT *******					********* 50% Decrease in MLDT *******			
Run #	AvoffTime	AvOnTime	MTBBR	Ao	AvoffTime	AvOnTime	MTBBR	Ao
1	175.09	562.5	758.67	0.7626	152.44	508.99	645.3	0.7695
2	219.48	633.91	826.73	0.7428	193.36	630.35	775.26	0.7653
3	195.04	576.99	730.29	0.7474	168.47	561.77	730.24	0.7693
4	178.14	639.73	769.76	0.7822	147.4	682.35	829.76	0.8224
5	186.48	633.3	846.22	0.7725	182.12	563.63	750.43	0.7558
6	170.26	593.88	742.3	0.7772	157.19	481.74	670	0.7540
7	208.7	503.27	711.98	0.7069	196.44	602.8	723.12	0.7542
8	223.76	572.85	730.22	0.7191	194.41	631.98	734.57	0.7648
9	182.33	876.75	1103.21	0.8278	145.44	825.33	1008.11	0.8502
10	166.76	808.59	975.35	0.8290	161.63	749.47	852.32	0.8226
Mean	**190.60**	**640.18**	**819.47**	**0.7668**	**169.89**	**623.84**	**771.91**	**0.7828**
S.E.	**6.45**	**36.49**	**40.16**	**0.01283**	**6.36**	**33.54**	**33.00**	**0.01**

********* 60% Decrease in MLDT *******					********* 70% Decrease in MLDT *******			
Run #	AvoffTime	AvOnTime	MTBBR	Ao	AvoffTime	AvOnTime	MTBBR	Ao
1	126.66	514.49	656.79	0.8024	107.96	506.17	614.13	0.8242
2	158.38	636.99	771.98	0.8009	134.49	578.48	712.97	0.8114
3	159.89	632.61	709.08	0.7983	129.19	517.15	616.97	0.8001
4	143.12	819.59	869.54	0.8513	116.04	551.09	650.86	0.8261
5	148.4	582.05	710.7	0.7968	130.64	658.44	766.54	0.8344
6	148.26	540.33	640.54	0.7847	127.57	610.85	681.62	0.8272
7	155.63	556.07	711.71	0.7813	133.33	620.52	659.62	0.8231
8	169.69	538.99	658.66	0.7606	127.43	563.56	658.08	0.8156
9	154.01	885.97	1039.97	0.8519	120.86	909.29	991.99	0.8827
10	130.9	628.14	737.96	0.8276	111.06	800.93	853.15	0.8782
Mean	**149.49**	**633.52**	**750.69**	**0.8056**	**123.86**	**631.65**	**720.59**	**0.8323**
S.E.	**4.17**	**39.28**	**38.40**	**0.00939**	**2.96**	**40.80**	**37.93**	**0.00858**

********* 80% Decrease in MLDT *******					********* 90% Decrease in MLDT *******			
Run #	AvoffTime	AvOnTime	MTBBR	Ao	AvoffTime	AvOnTime	MTBBR	Ao
1	82.09	474.96	545.68	0.8526	67	517.23	536.53	0.8853
2	110.04	568.84	661.91	0.8379	78.83	550.71	574.8	0.8748
3	106.71	601.35	671.75	0.8493	80.65	541.88	571.72	0.8704
4	86.86	592.1	662.4	0.8721	66.04	550.58	576.40	0.8929
5	102.97	718.78	751.32	0.8747	67.6	547.65	575.98	0.8901
6	99.07	570.54	653.28	0.8520	70.91	548.21	605.04	0.8855
7	97.03	623.66	669.21	0.8654	79.57	549.31	550.36	0.8735
8	97.98	530.93	600.33	0.8442	71.92	595.22	635.37	0.8922
9	101.2	840.41	878.84	0.8925	65.92	693.24	759.17	0.9132
10	87.12	650.34	717.53	0.8819	63.35	697.62	739.84	0.9168
Mean	**97.11**	**617.19**	**681.23**	**0.8623**	**71.18**	**579.17**	**612.52**	**0.8895**
S.E.	**2.88**	**32.38**	**28.27**	**0.00562**	**2.01**	**20.28**	**24.42**	**0.00494**

The following is the simulation output for manipulations in percent of *organic* repair.

	********* 10% Organic Repair *******				********* 20% Organic Repair *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	333.02	335.76	592.79	0.5021	357.6	353.15	611.57	0.4969
2	384.02	495.38	694.26	0.5633	357.11	463.09	709.43	0.5646
3	304.38	422.55	672.41	0.5813	304.69	420.45	670.75	0.5798
4	257.62	422.95	577	0.6215	256.89	417.97	584.88	0.6193
5	287.43	403.23	640.13	0.5838	276.58	440.3	680.12	0.6142
6	253.02	379.66	565.38	0.6001	254.7	365.13	555.27	0.5891
7	293.35	340.44	552.88	0.5372	285.66	406.83	572.05	0.5875
8	347.51	324.94	624.42	0.4832	342.05	365.21	658.49	0.5164
9	283.38	539.28	797.73	0.6555	304.01	627.99	899.86	0.6738
10	264.31	306.05	468.51	0.5366	254.76	330.37	516.3	0.5646
MEAN	**300.80**	**397.02**	**618.55**	**0.5665**	**299.41**	**419.05**	**645.87**	**0.5806**
S.E.	**13.41**	**24.04**	**28.53**	**0.01682**	**12.95**	**26.71**	**34.29**	**0.01602**

	********* 30% Organic Repair *******				********* 40% Organic Repair *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	335.11	346.6	575.66	0.5084	322.86	519.16	690.89	0.6166
2	337.98	562.27	791.13	0.6246	364.03	719.1	896.45	0.6639
3	347.99	594.91	800.03	0.6309	274.65	493.61	752	0.6425
4	235.21	438.68	641.02	0.6510	258.3	560.81	794.29	0.6847
5	276.58	486.99	786.7	0.6378	274.86	481.54	778.65	0.6366
6	227.98	475.45	658.17	0.6759	283.32	514.22	713.59	0.6448
7	263.65	402.28	665.93	0.6041	295.96	476.47	693.21	0.6168
8	333.43	402.34	697.04	0.5468	297.59	478.81	713.46	0.6167
9	270.75	766.06	1036.81	0.7389	267.98	745.49	975.94	0.7356
10	271.81	425.92	589.2	0.6104	250.22	446.81	697.03	0.6410
MEAN	**290.05**	**490.15**	**724.17**	**0.6229**	**288.98**	**543.60**	**770.55**	**0.6499**
S.E.	**14.146**	**38.779**	**43.149**	**0.02020**	**10.66**	**32.95**	**30.41**	**0.01173**

	********* 50% Organic Repair *******				********* 60% Organic Repair *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	255.48	541.35	796.83	0.6794	250.65	597.31	847.96	0.7044
2	360.03	722.99	962.69	0.6676	262.57	692.22	922.18	0.7250
3	284.9	648.06	845.5	0.6946	249.58	754.22	1043.95	0.7514
4	254.96	645.42	900.38	0.7168	297.19	1005.28	1189.21	0.7718
5	273.69	591.47	865.16	0.6837	272.64	672.46	1102.9	0.7115
6	257.77	474.86	712.83	0.6482	231.89	595.43	854.01	0.7197
7	310.86	497.33	784.42	0.6154	278.14	497.94	851.18	0.6416
8	318.33	540.37	858.71	0.6293	350.3	897.52	1091.84	0.7193
9	260.1	725.02	1063.94	0.7360	256.34	805.73	1062.08	0.7586
10	248.47	638.61	917.67	0.7199	251.34	828.66	1173.91	0.7673
MEAN	**282.46**	**602.55**	**870.81**	**0.6791**	**270.06**	**734.68**	**1013.92**	**0.7271**
S.E.	**11.52**	**27.85**	**31.18**	**0.01257**	**10.59**	**48.76**	**42.37**	**0.01220**

********* 70% Organic Repair *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	247.52	771.83	1060.12	0.7572
2	278.07	782.29	1152.57	0.7378
3	286.96	976.69	1326.83	0.7729
4	305.55	898.71	1261.6	0.7463
5	273.2	780.45	1254.34	0.7407
6	260.53	976.74	1237.28	0.7894
7	298.49	716.67	942.65	0.7060
8	295.67	809.66	1205.82	0.7325
9	285.1	1080.44	1438.34	0.7912
10	210.83	1163.31	1616.64	0.8466
MEAN	**274.19**	**895.68**	**1249.62**	**0.7621**
S.E.	**8.97**	**47.12**	**59.45**	**0.01256**

********* 80% Organic Repair *******			
AvOffTime	AvOnTime	MTBBR	Ao
186.09	660.47	1192.89	0.7802
239.3	1224.95	1647.28	0.8366
196.13	1537.34	2000.16	0.8869
279.44	1283.58	1771.43	0.8212
312.62	944.97	1389.97	0.7514
299.57	1019.77	1552.17	0.7729
351.6	1016.99	1443.17	0.7431
300.49	964.27	1324.98	0.7624
215.15	1498.09	2284.32	0.8744
167.29	1324.16	2440.56	0.8878
254.77	**1147.46**	**1704.69**	**0.8117**
19.73	**86.65**	**132.05**	**0.01806**

********* 90% Organic Repair *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	169.85	905.76	1442.99	0.8421
2	186.13	2240.69	2599.87	0.9233
3	215.42	2260.41	3000.14	0.9130
4	243.15	1791.91	3306.98	0.8805
5	169.63	985.01	2213.05	0.8531
6	285.08	1360.43	2025.24	0.8268
7	220.25	1069.19	2285.60	0.8292
8	218.05	1548.31	2355.15	0.8766
9	211.16	1697.25	2968.65	0.8894
10	152.15	2172.58	5579.34	0.9346
MEAN	**207.09**	**1603.15**	**2777.70**	**0.8768**
S.E.	**6.28**	**22.78**	**33.50**	**0.19686**

APPENDIX D. CASE 3 OUTPUT

The following is the simulation output for manipulations in Weibull shape parameter.

********* Base Case *******					********* Shape of 0.8 *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	260.62	373.75	579.21	0.5892	253.96	187.66	428.13	0.4249
2	292.49	351.86	585.77	0.5461	313.88	221.27	485.61	0.4135
3	329.04	300.87	552.78	0.4776	332.64	203.65	420.06	0.3797
4	273.25	386.53	643.69	0.5859	252.41	235.32	478.86	0.4825
5	271.90	317.99	589.89	0.5391	299.18	153.07	444.29	0.3385
6	279.39	399.66	575.72	0.5886	253.9	204.25	415.95	0.4458
7	319.18	406.75	653.34	0.5603	315.47	196.36	522.07	0.3837
8	318.27	351.59	622.01	0.5249	284.79	227.39	468.03	0.4440
9	265.08	533.48	798.56	0.6681	291.86	307.44	507.1	0.5130
10	247.35	374.1	636.61	0.6020	264.68	185	434.69	0.4114
MEAN	**285.66**	**379.66**	**623.76**	**0.5682**	**286.28**	**212.14**	**460.48**	**0.4237**
S.E.	**8.83**	**20.13**	**22.09**	**0.01625**	**9.23**	**12.97**	**11.82**	**0.01612**

********* Shape of 1.2 *******					********* Shape of 1.6 *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	255.48	541.35	796.83	0.6794	255.56	1140.38	1560.17	0.8169
2	360.03	722.99	962.69	0.6676	373.3	1441.06	1693.4	0.7943
3	284.9	648.06	845.5	0.6946	300.5	1453.76	1644.62	0.8287
4	254.96	645.42	900.38	0.7168	227.4	2154.22	2381.61	0.9045
5	273.69	591.47	865.16	0.6837	275.25	1497.76	1662.20	0.8448
6	257.77	474.86	712.83	0.6482	317.34	1600.41	1797.89	0.8345
7	310.86	497.33	784.42	0.6154	291.28	1153.01	1444.29	0.7983
8	318.33	540.37	858.71	0.6293	260.04	1139.59	1477.39	0.8142
9	260.1	725.02	1063.94	0.7360	310.62	2685.14	2995.76	0.8963
10	248.47	638.61	917.67	0.7199	234.49	2807	3041.5	0.9229
MEAN	**282.46**	**602.55**	**870.81**	**0.6791**	**284.58**	**1707.23**	**1969.88**	**0.8455**
S.E.	**11.519**	**27.854**	**31.185**	**0.01257**	**13.84**	**197.39**	**193.32**	**0.01457**

********* Shape of 2.0 *******				
Run #	AvOffTime	AvOnTime	MTBBR	Ao
1	303.94	1738.35	1896.41	0.8512
2	279.45	2704.05	2983.5	0.9063
3	222.62	2703.71	2926.33	0.9239
4	235.46	3189.47	3424.93	0.9313
5	228.69	2441.11	2669.79	0.9143
6	224.57	2286.97	2511.54	0.9106
7	290.85	3752.96	4043.81	0.9281
8	318.1	4283.5	4601.6	0.9309
9	406.21	4865.32	5271.54	0.9229
10	120.13	3681.85	4435.64	0.9684
MEAN	**263.00**	**3164.73**	**3476.51**	**0.9188**
S.E.	**23.97**	**307.52**	**339.23**	**0.00925**

APPENDIX E. CASE 4 OUTPUT

The following is the simulation output for manipulations in Transit Delay.

********* Base Case *******					*** Transit Delay of 48 hours *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	260.62	373.75	579.21	0.5892	304.75	378.41	555.07	0.5539
2	292.49	351.86	585.77	0.5461	332.39	330.14	552.11	0.4983
3	329.04	300.87	552.78	0.4776	376	298.73	515.97	0.4427
4	273.25	386.53	643.69	0.5859	322.05	454.74	644.17	0.5854
5	271.90	317.99	589.89	0.5391	318.9	310.48	562.43	0.4933
6	279.39	399.66	575.72	0.5886	308.01	425.95	600.51	0.5804
7	319.18	406.75	653.34	0.5603	372.85	378.32	611.41	0.5036
8	318.27	351.59	622.01	0.5249	373.85	381.89	615.14	0.5053
9	265.08	533.48	798.56	0.6681	317.47	549.81	792.94	0.6340
10	247.35	374.1	636.61	0.6020	298.5	468.41	651.88	0.6108
MEAN	**285.66**	**379.66**	**623.76**	**0.5682**	**332.48**	**397.69**	**610.16**	**0.5408**
S.E.	**8.83**	**20.13**	**22.09**	**0.01625**	**9.59**	**24.76**	**24.49**	**0.01933**

**** Transit Delay of 72 hours *******					**** Transit Delay of 96 hours *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	350.42	348.87	512.5	0.4989	378.28	359.94	513.75	0.4876
2	365.08	339.1	608.15	0.4816	404.24	355.42	556.06	0.4679
3	416.6	370.58	491.99	0.4708	564.26	344.28	495.57	0.3789
4	316.06	395.25	600.67	0.5557	376.59	416.65	616.97	0.5253
5	397.84	323.45	540.97	0.4484	477.53	320.10	537.18	0.4013
6	325.14	420.06	586.65	0.5637	393.87	376.01	513.25	0.4884
7	469.65	433.37	609.01	0.4799	430.15	333.38	564.35	0.4366
8	377.44	306.77	652.68	0.4484	402.39	320.13	556.94	0.4431
9	365.1	387.62	693.29	0.5150	423.37	442.86	666.33	0.5113
10	347.83	405.14	598.96	0.5381	396.67	419.67	519.29	0.5141
MEAN	**373.12**	**373.02**	**589.49**	**0.5000**	**424.74**	**368.84**	**553.97**	**0.4654**
S.E.	**14.407**	**13.408**	**19.295**	**0.01323**	**18.08**	**13.85**	**16.63**	**0.01563**

********* 120 hour transit delay *******					********* 144 hour transit delay *******			
Run #	AvOffTime	AvOnTime	MTBBR	Ao	AvOffTime	AvOnTime	MTBBR	Ao
1	407.67	337.47	515.98	0.45289	441.87	323.9	479.71	0.42298
2	419.97	397.84	617.9	0.48647	581.49	399.13	564.73	0.40702
3	548.06	341.69	485.49	0.38403	529.94	277.1	457.32	0.34335
4	377.79	379.11	606.91	0.50087	468.96	356.48	552.53	0.43186
5	481.07	229.33	505.48	0.32282	615.75	395.7	523.25	0.39122
6	423	369.84	528.56	0.46647	458.07	256.59	498.91	0.35904
7	566.36	330.05	553.1	0.36819	515.14	357.2	551.9	0.40947
8	466.63	291.56	533.24	0.38455	518.07	347.69	536.77	0.4016
9	459.76	396.87	663.89	0.46329	560.69	530.61	699.94	0.48622
10	422.84	333.33	523.5	0.44081	535.46	430.53	516.09	0.44569
MEAN	**457.32**	**340.71**	**553.41**	**0.42704**	**522.54**	**367.49**	**538.12**	**0.40985**
S.E.	**19.245**	**16.242**	**18.092**	**0.01847**	**17.464**	**24.803**	**20.944**	**0.01300**

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